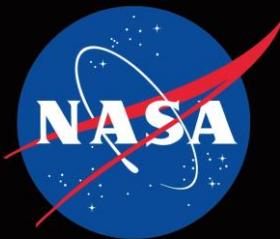


Ground-based Radar Observations of Didymos

S. P. Naidu, L. A. M. Benner, M. Brozovic, J. D. Giorgini, S. J. Ostro, M.
C. Nolan, J. L. Margot, P. Pravec, P. Scheirich, A. Virkki,
D. J. Scheeres

Jet Propulsion Laboratory, California Institute of Technology



Part 1: Physical characterization of Didymos

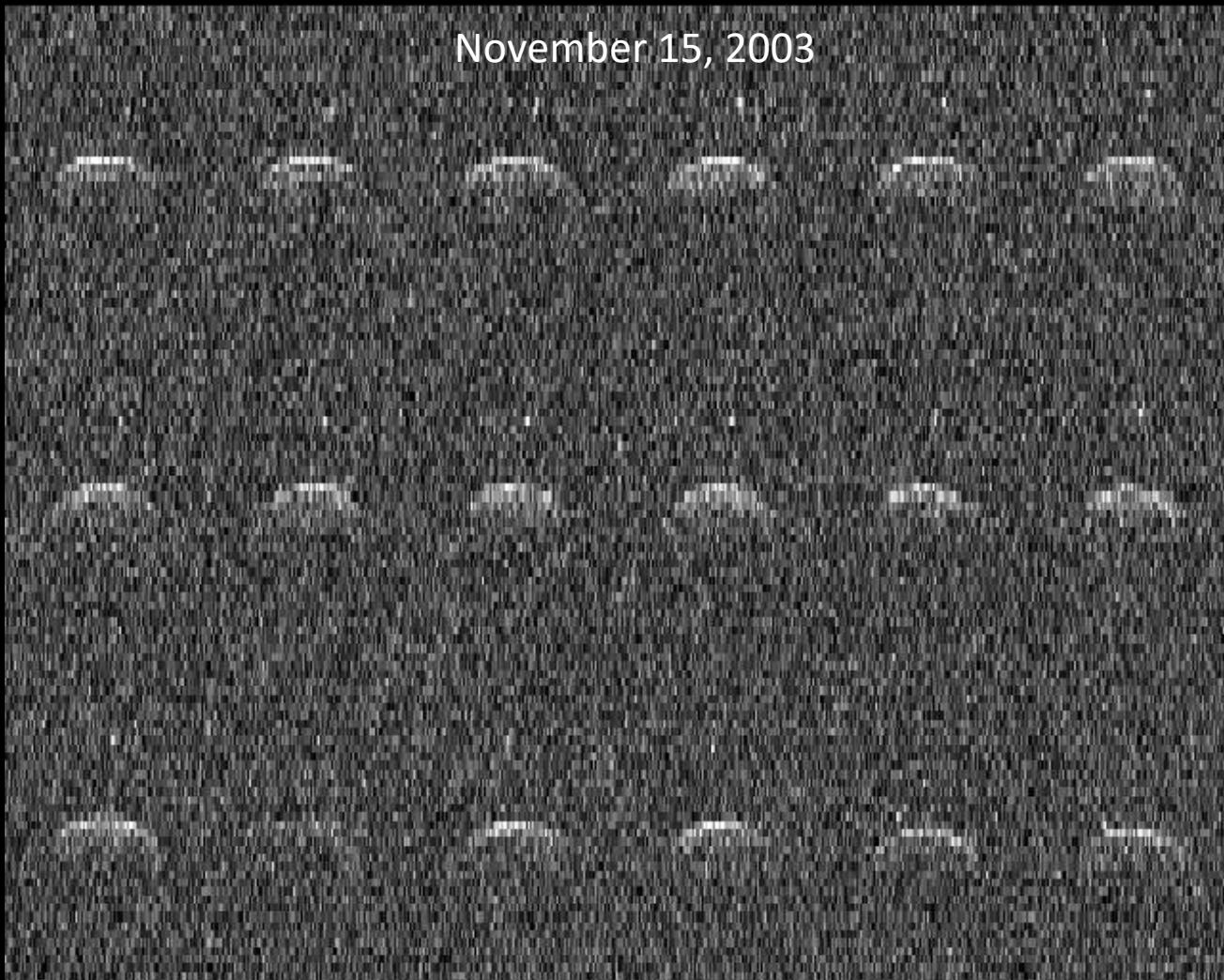
Data

- 2003 radar observations
 - Goldstone on Nov 14, 15 (range resolution 75 m/pixel, sub-radar latitude -30 degrees)
 - Arecibo on Nov 23, 24, 26 (range resolution 15m/pixel, sub-radar latitude -7 to -12 degrees)
- 2003 lightcurve observations (Pravec et al. 2006)
 - Nov 20-24, Nov 26- Dec 04, Dec 16-20 (sub-radar latitudes < +9 degrees)

Goldstone images

November 15, 2003

Range (75 m/pixel) →



Doppler Frequency (0.5 Hz/pixel) →

Arecibo images

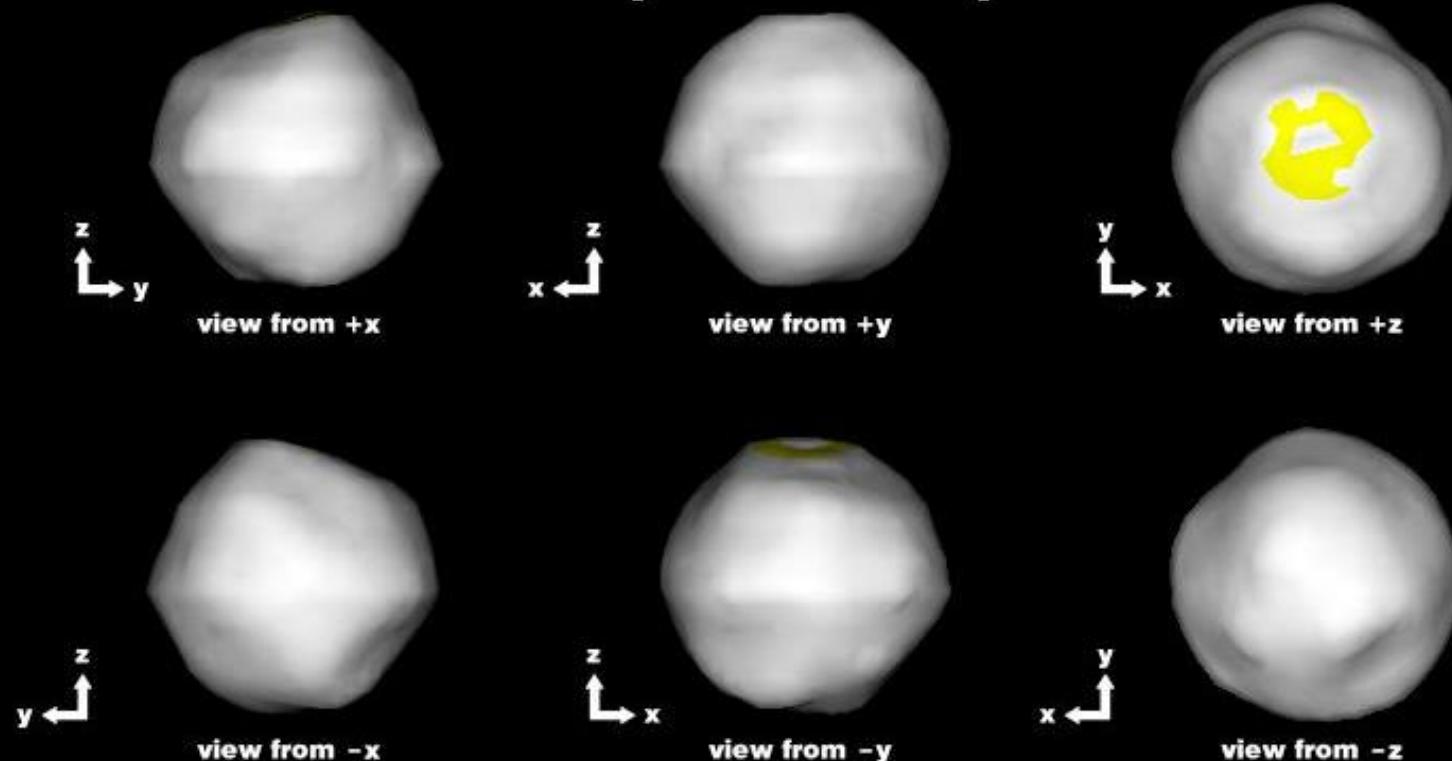
November 24, 2003

Range (15 m/pixel) →

Doppler frequency (0.3 Hz/pixel) →

Primary shape

1 km



Dimensions: 797 m x 783 m x 761 m (Uncertainty is 10%
in x, y and 15% in z dimension)

Volume equivalent diameter: 780 m (+/- 12%)

Model facets: 1996

Model resolution: 50 m

Selected radar fits

Arecibo
Nov 23

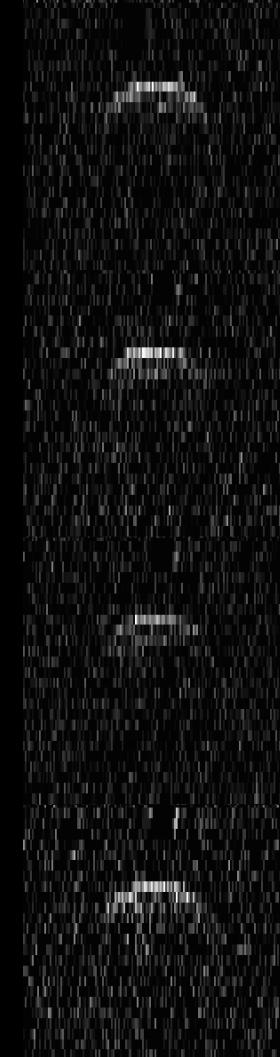


Data

Fit

Model

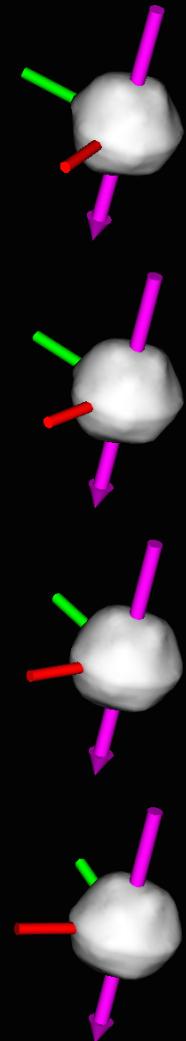
Goldstone
Nov 15



Data

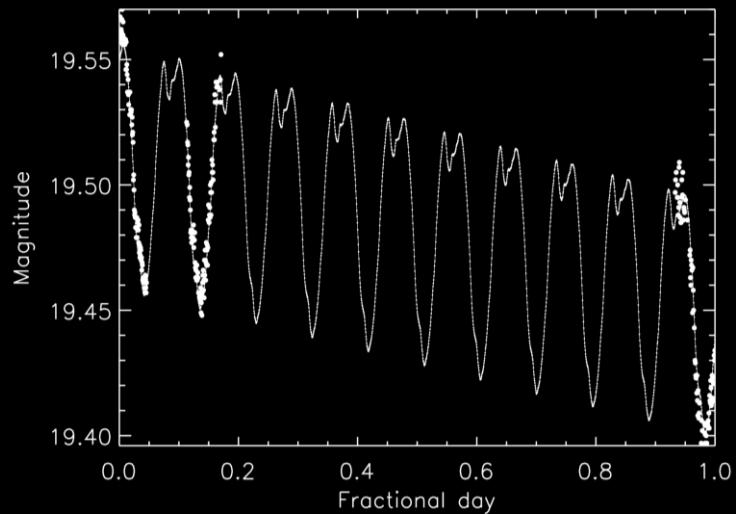
Fit

Model

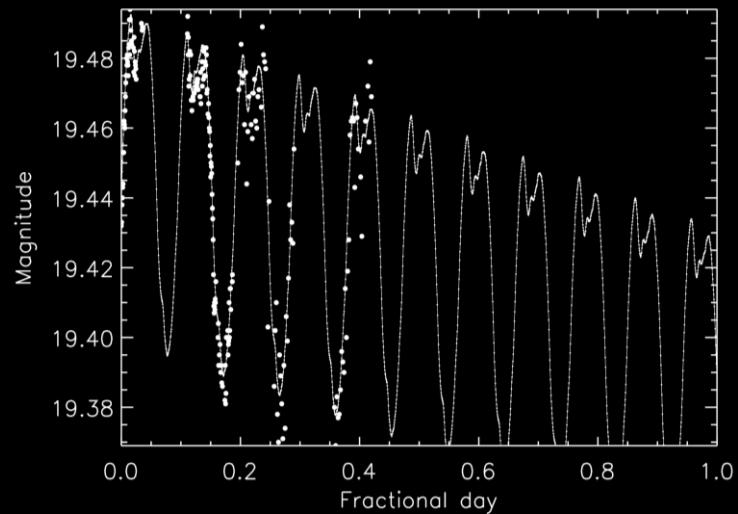


Lightcurve fits (2003)

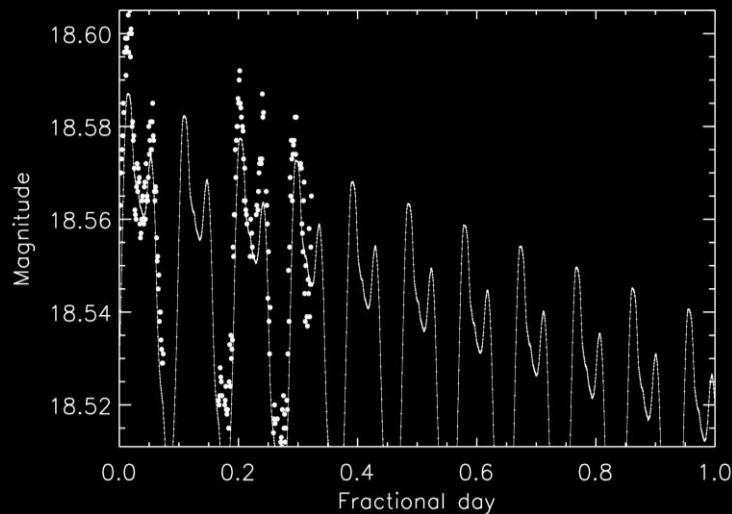
Nov 20



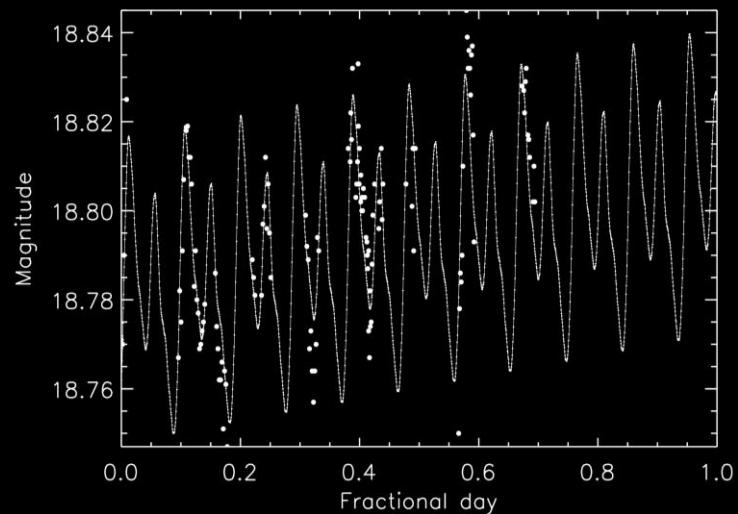
Nov 21



Nov 29



Dec 18



Secondary

Arecibo images

Nov 23, 2003
(47 runs)

Simple stacking

Shift & stack

Secondary

Nov 23



47 runs

Resolution: 15 m x 0.0375 Hz

Nov 24



54 runs

Resolution: 15 m x 0.0375 Hz

Secondary

Nov 23

R=60-90 m
P=9-12 h

Nov 24



47 runs

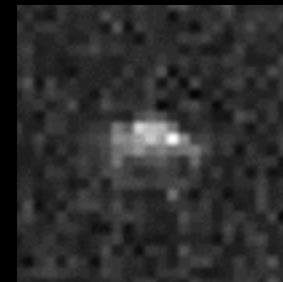
Resolution: 15 m x 0.0375 Hz

54 runs

Resolution: 15 m x 0.0375 Hz

Secondary shape

Nov 23 (Arecibo images)



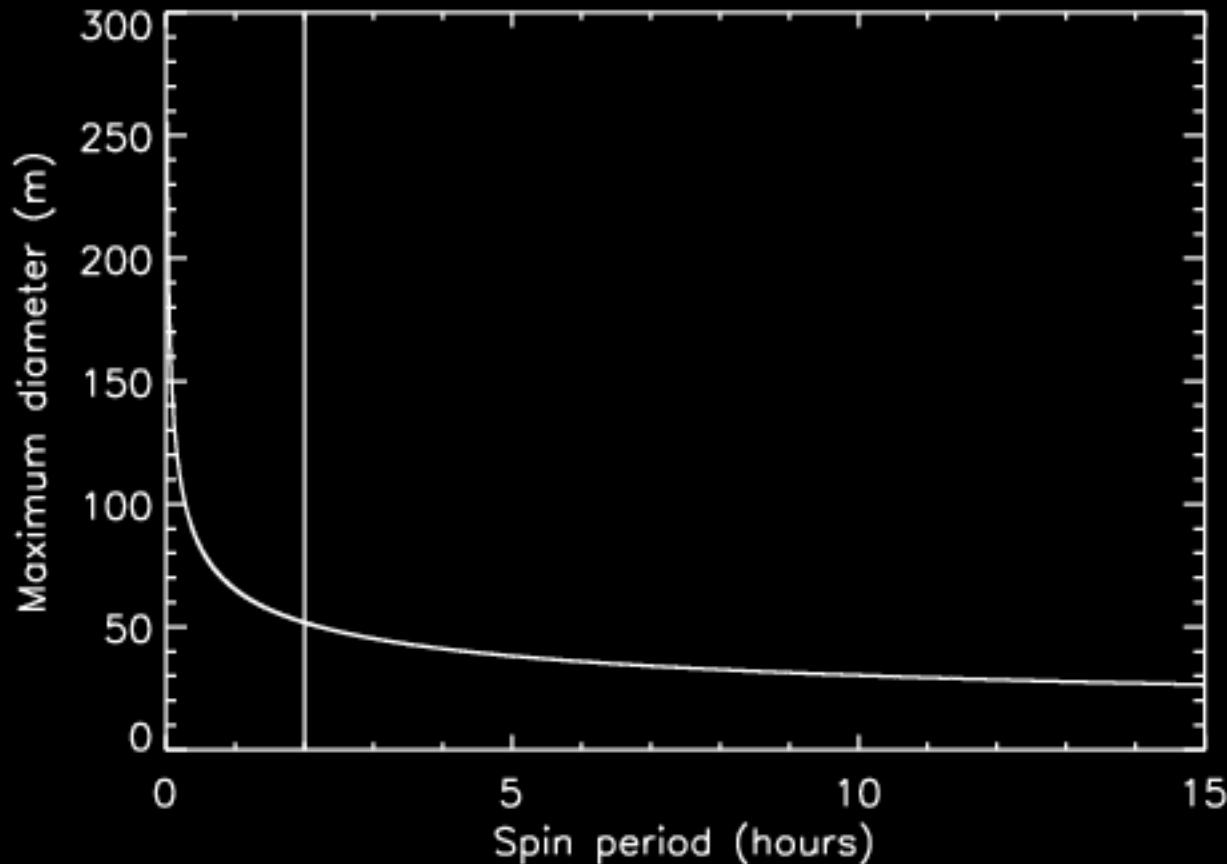
Nov 24 (Arecibo images)



Image resolutions: 15 m x 0.0375 Hz

Each image is integrated over 15 degrees of rotation.

3σ limits on tertiary



If $P > 2$ hours, $D < 50$ meters.

Mutual orbit

- Data: 108 delay and Doppler measurements from Arecibo and Goldstone images and spectra.
 - Primary COM was modeled using the shape model.
 - Secondary COM was assumed to be 75 m behind leading edge.
- Initial conditions: Scheirich & Pravec (2009)
- Fit values: $a = 1188$ m, $e < 0.045$, $P = 11.92$ hours, $M=5.377e11$ kg (+/- 10%), density = 2164 kg/m³ (+/- 30%)
 - Consistent with values derived from Scheirich & Pravec (2009).
 - Spin pole < 2 degrees away from Scheirich & Pravec (2009)

Part 1: Summary

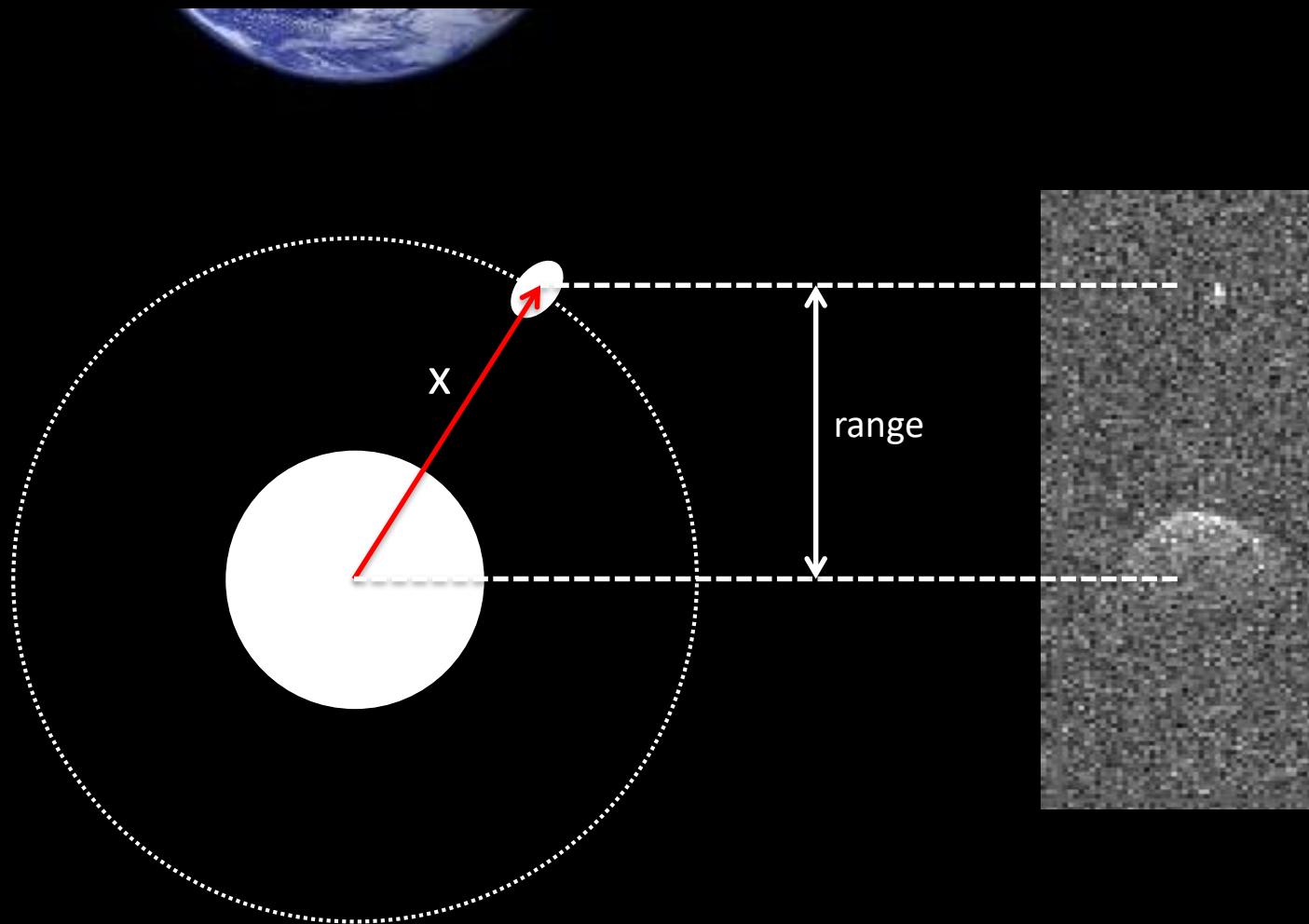
- Primary shape and dimensions (797 m x 783 m x 761 m: Uncertainties +/- 10% in x, y and +/-15% in z)
- Secondary shape is not round. It's diameter is between 120 and 180 m and spin is most likely synchronous.
- Any potential tertiary would most likely be smaller than 50 m in diameters unless it is spinning faster than 2 hours.
- Radar derived mutual orbit is consistent with that obtained by Scheirich and Pravec (2009).

Part 2: Using Ground-based Radar to Detect Changes in the Didymos Binary Orbit Due to DART Impact

Estimating signal-to-noise ratios in 2022

- We used the size, spin period, and the radar albedo derived from 2003 for estimating the SNRs in 2022.
- Close approach distance in 2022 will be about 1.5 times that in 2003.
 - Setups identical to those used in 2003 will yield 1/6th the SNRs.
 - We can boost the signal/pixel by compromising on resolution.
- At Arecibo, we should be able to obtain delay-Doppler images and echo power spectra.
- Goldstone should be able to obtain echo power spectra but if we use Green Bank to receive, we will most likely be able to obtain images as well.
- Finest images will most likely have resolutions of 75 m, which should allow us to see the primary as well as the secondary.

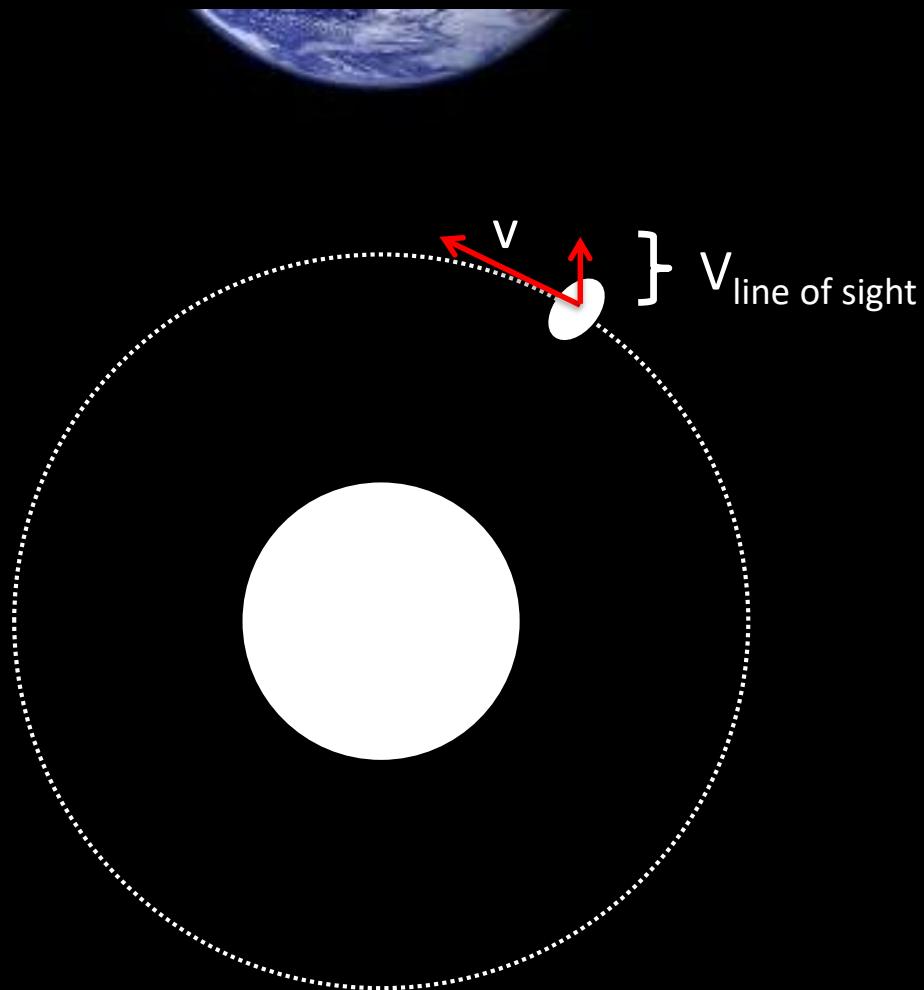
Radar observables (range)



Pole-on view of a binary system

Radar delay-Doppler image

Radar observables (Doppler)

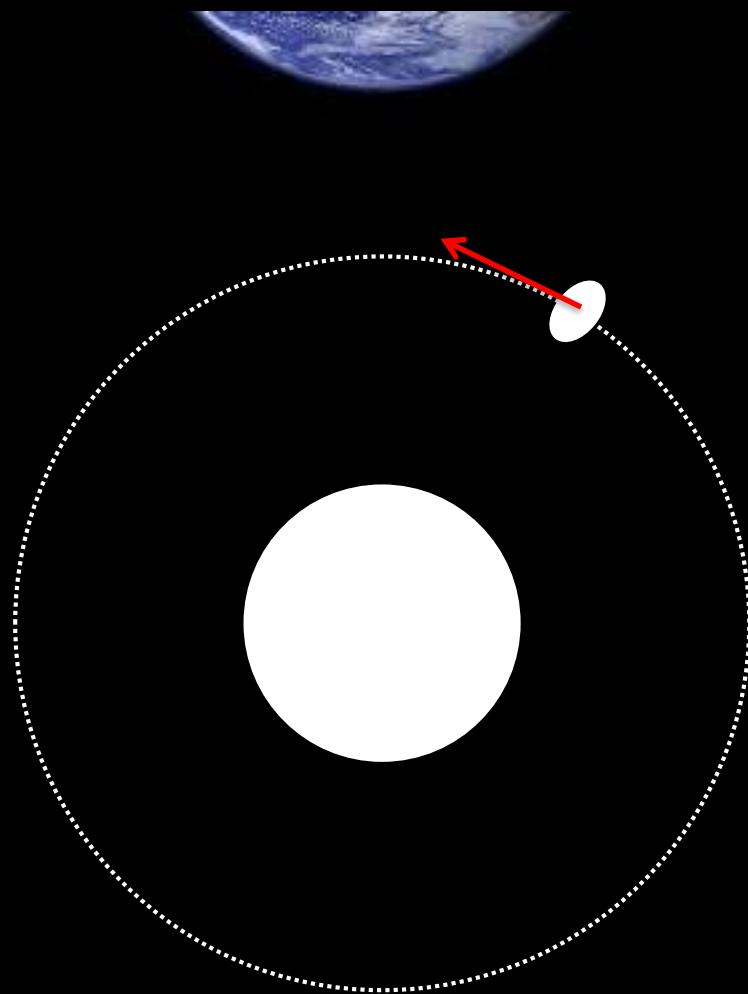


Pole-on view of a binary system



Radar delay-Doppler image

Radar observables (Doppler)



Pole-on view of a binary system



Radar delay-Doppler image

Predicted SNRs at Goldstone and Green Bank for the satellite

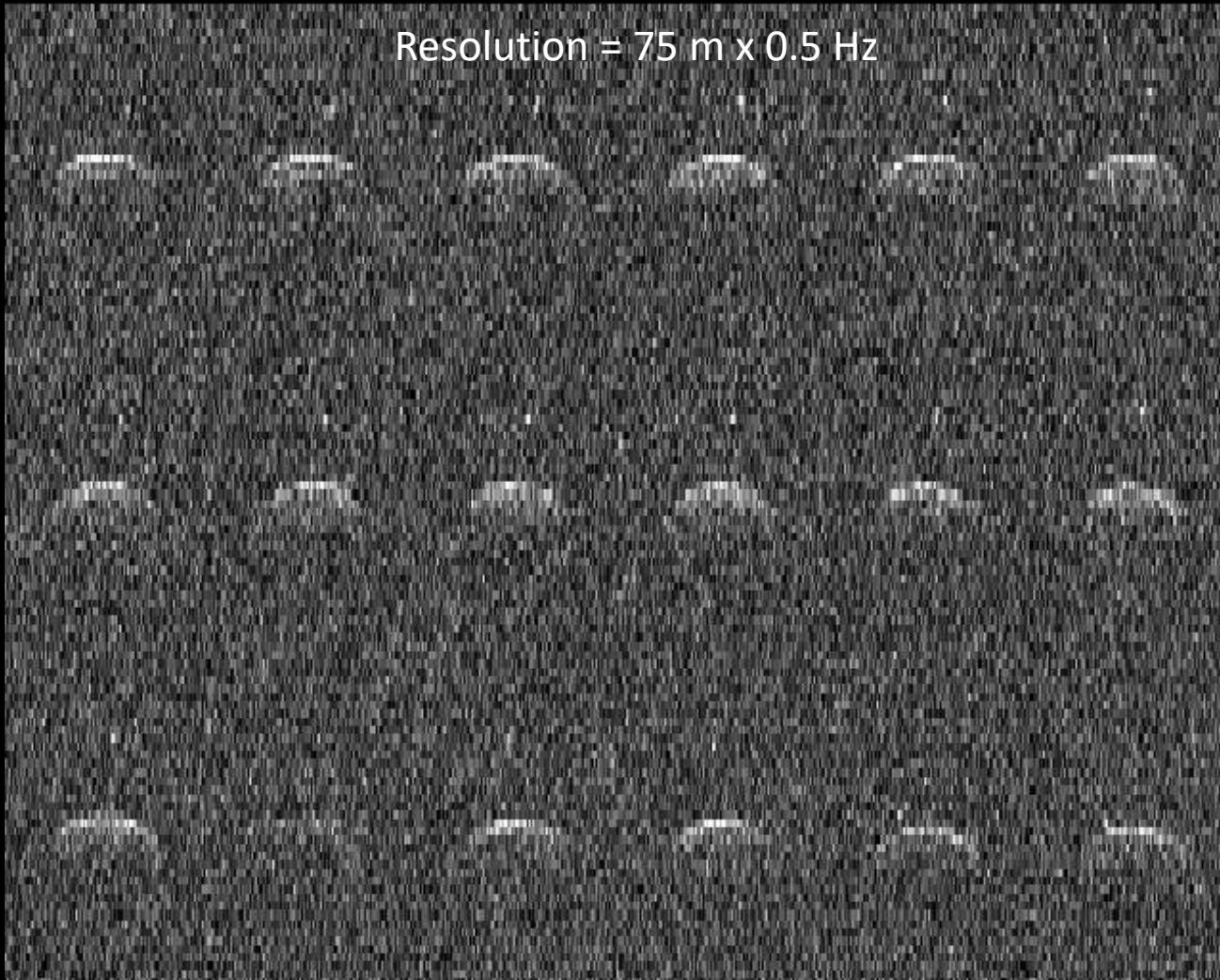
| UTC date | dist (au) | Dec. (deg) | SNR/ day | SNR/ run | SNR/ (DSS-14 → Green Bank) |
|-------------|--------------|---------------|-------------|-------------|-------------------------------|
| 2022 Sep 25 | 0.078 | -34 | 6 | 1 | |
| 2022 Sep 26 | 0.076 | -34 | 9 | 1 | |
| 2022 Sep 27 | 0.075 | -33 | 11 | 2 | |
| 2022 Sep 28 | 0.074 | -32 | 12 | 2 | |
| 2022 Sep 29 | 0.073 | -32 | 14 | 2 | |
| 2022 Sep 30 | 0.072 | -31 | 16 | 2 | |
| 2022 Oct 01 | 0.072 | -30 | 18 | 2 | 5 |
| 2022 Oct 02 | 0.072 | -28 | 19 | 2 | 5 |
| 2022 Oct 03 | 0.071 | -27 | 20 | 2 | 5 |
| 2022 Oct 04 | 0.071 | -26 | 21 | 2 | 5 |
| 2022 Oct 05 | 0.071 | -25 | 22 | 2 | 5 |
| 2022 Oct 06 | 0.072 | -23 | 23 | 2 | 5 |
| 2022 Oct 07 | 0.072 | -22 | 23 | 2 | 5 |
| . | | | | | |
| 2022 Oct 14 | 0.078 | -12 | 19 | 2 | 5 |
| 2022 Oct 15 | 0.080 | -11 | 18 | 2 | 5 |
| . | | | | | |
| 2022 Oct 21 | 0.090 | -4 | 12 | 1 | 2 |
| 2022 Oct 22 | 0.092 | -3 | 11 | 1 | 2 |
| 2022 Oct 23 | 0.094 | -2 | 10 | 1 | 2 |
| 2022 Oct 24 | 0.095 | -1 | 9 | 1 | 2 |

Predicted Arecibo SNRs for the satellite

| UTC date | | dist (au) | Dec. (deg) | SNR/ day | SNR/ run |
|-------------|--|--------------|---------------|-------------|-------------|
| 2022 Oct 24 | | 0.095 | -1 | 44 | 13 |
| 2022 Oct 25 | | 0.097 | 0 | 55 | 13 |
| 2022 Oct 26 | | 0.099 | +1 | 61 | 14 |
| 2022 Oct 27 | | 0.101 | +2 | 64 | 14 |
| 2022 Oct 28 | | 0.103 | +3 | 65 | 14 |
| 2022 Oct 29 | | 0.105 | +4 | 65 | 13 |
| 2022 Oct 30 | | 0.107 | +4 | 63 | 12 |
| 2022 Oct 31 | | 0.110 | +5 | 60 | 12 |
| 2022 Nov 01 | | 0.112 | +6 | 58 | 11 |
| 2022 Nov 02 | | 0.114 | +7 | 55 | 10 |
| 2022 Nov 03 | | 0.116 | +7 | 52 | 9 |
| 2022 Nov 04 | | 0.118 | +8 | 49 | 9 |
| 2022 Nov 05 | | 0.120 | +9 | 46 | 8 |
| 2022 Nov 06 | | 0.122 | +9 | 44 | 8 |
| 2022 Nov 07 | | 0.125 | +10 | 41 | 7 |
| 2022 Nov 08 | | 0.127 | +10 | 39 | 7 |
| . | | | | | |
| 2022 Dec 04 | | 0.181 | +22 | 10 | 2 |
| 2022 Dec 05 | | 0.183 | +22 | 10 | 2 |
| 2022 Dec 06 | | 0.185 | +22 | 9 | 2 |

Goldstone Images from 2003 Nov 15

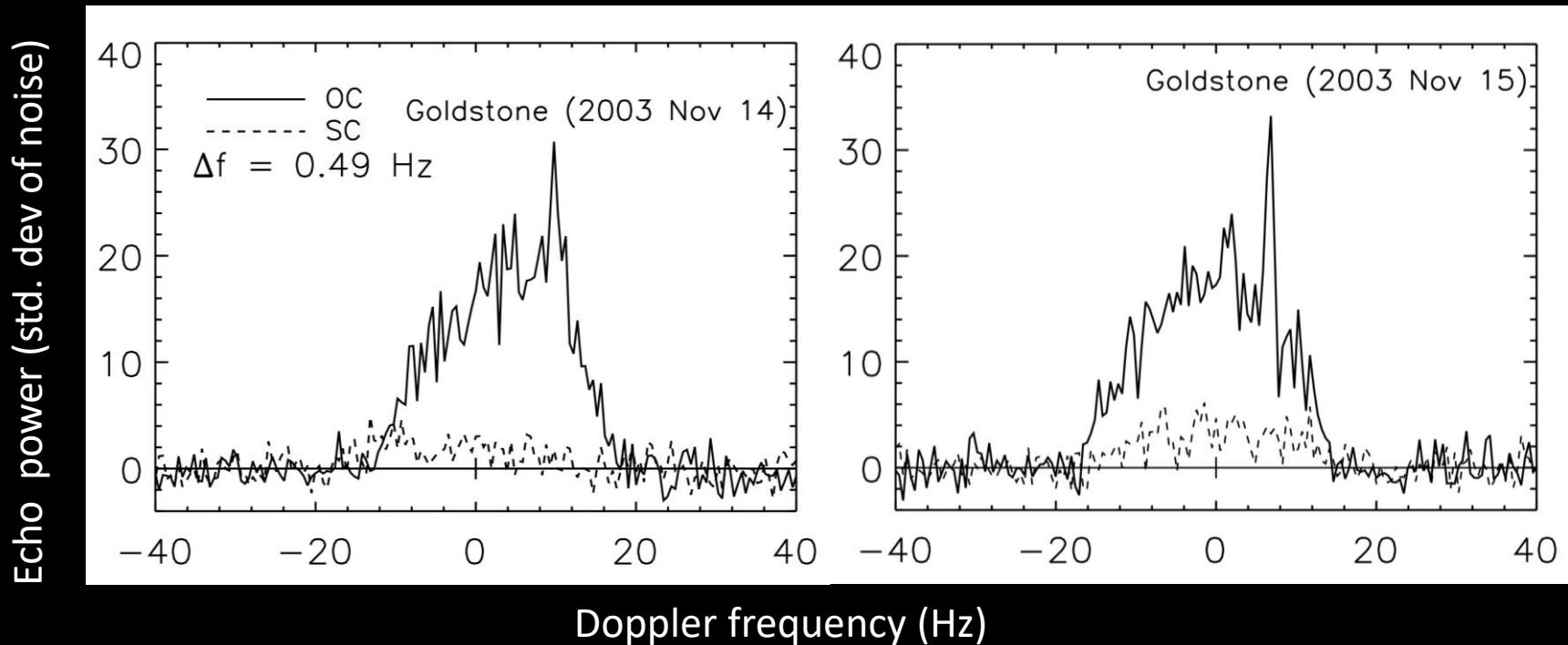
Range (75 m/pixel) →



Doppler Frequency (0.5 Hz/pixel) →

The highest Arecibo SNRs in 2022 will be 1.6x stronger than in these images.
The highest Goldstone → Green Bank SNRs will be about half of these.

Goldstone echo power spectra from 2003



The highest Arecibo SNRs in 2022 will be 1.6x stronger than in these images.
The highest Goldstone to Green Bank SNRs will be about half of these.

Arecibo Images from 2003 Nov 24

Range (15 m/pixel) →

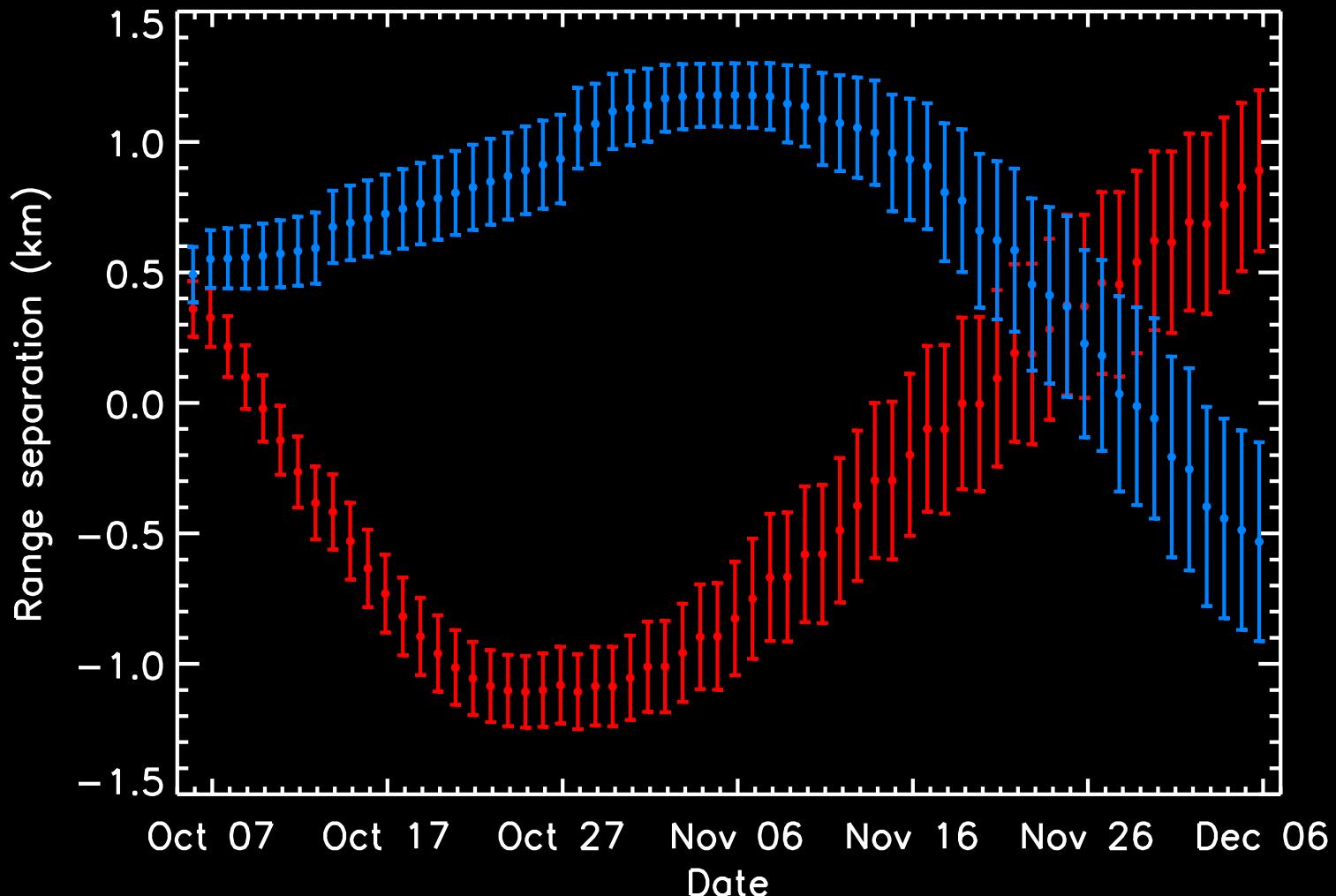


The strongest Arecibo SNRs in 2022 will be 1/6th of those shown here

Assumptions for range and Doppler displacement predictions

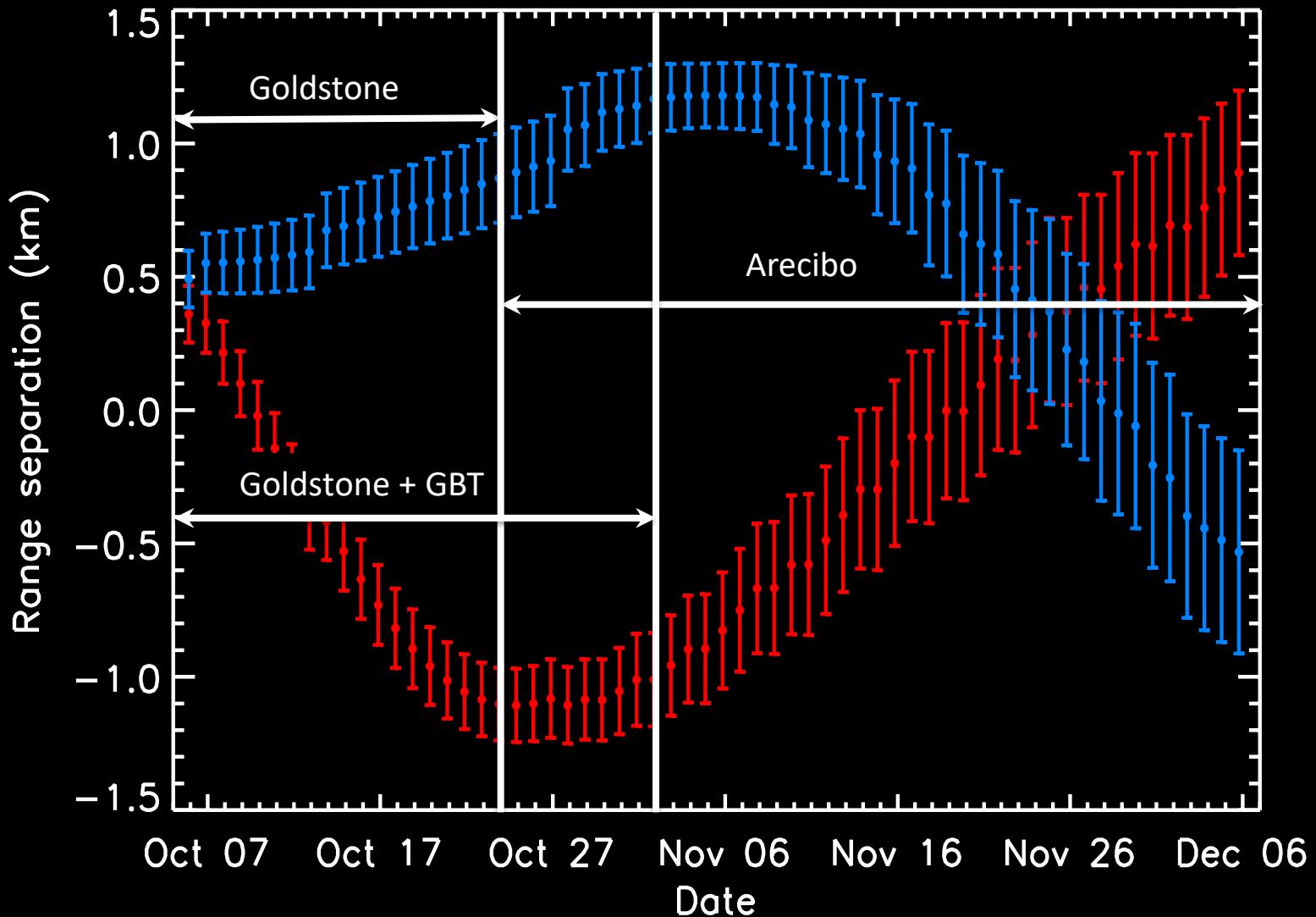
- An orbital period change of 7 minutes due to the DART impact.
- The orbit pole uncertainty of 10 degrees.
- The orbital period uncertainty of 0.004 hours.
- The orbital position uncertainty of 5 degrees on the day of the impact.
- Measurement errors in Doppler and range separations of +/- 1 Hz and +/- 100 m.

Range displacement predictions

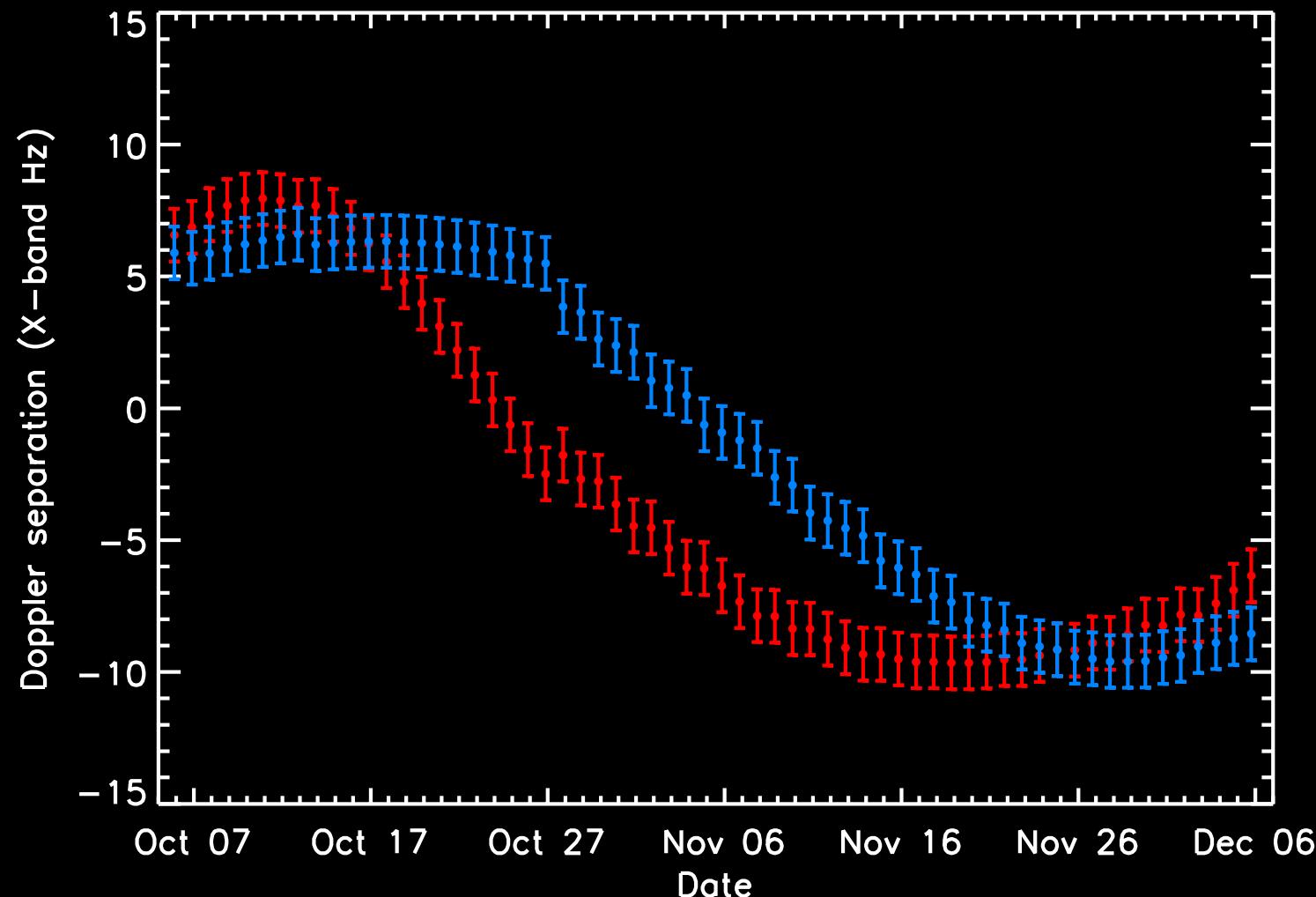


Red and blue points indicate modeled range separation measurements for the **unperturbed** and **perturbed** orbits respectively. Error bars include orbital and measurement uncertainties

Range displacement predictions

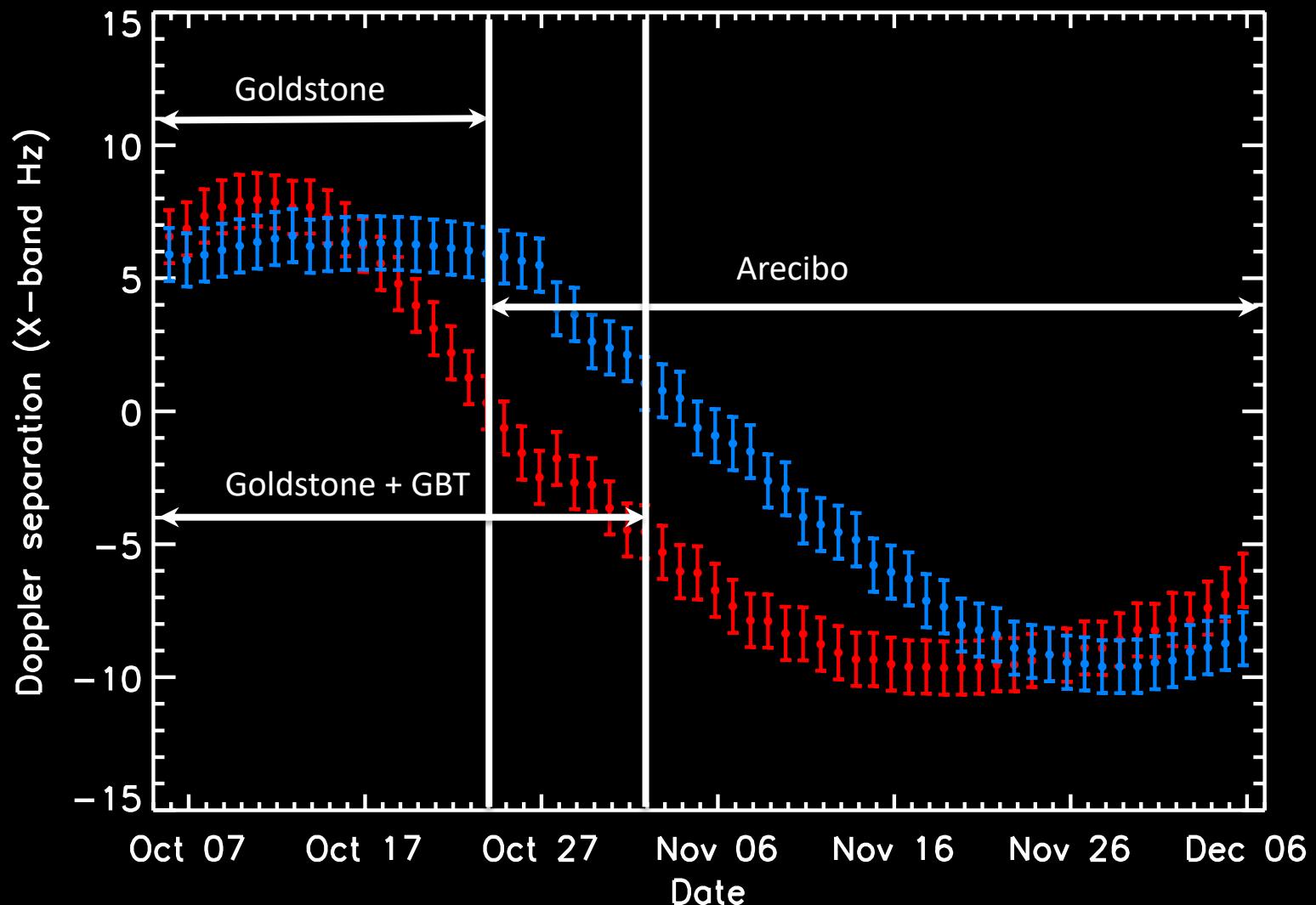


Doppler displacement predictions



Red and blue points indicate modeled Doppler separation measurements for the **unperturbed** and **perturbed** orbits respectively. Error bars include orbital and measurement uncertainties

Doppler displacement predictions



Part 2: Conclusions

- Arecibo signal-to-noise ratios in 2022 will be a factor of six lower than in 2003 but still strong enough for imaging.
 - Arecibo SNRs will still be about 60% higher than SNRs at Goldstone in 2003.
- The secondary will be detectable at Arecibo in delay-Doppler for about 2 weeks (Oct 24 to Nov 06) with SNRs comparable to those at Goldstone in 2003.
- Goldstone SNRs will be 1/4th of the values in 2003.
- If we transmit at Goldstone and receive at Green Bank, SNRs increase by 2.3 and the detectability of the satellite lengthens by about one week.
- Detection of the secondary in delay-Doppler images using Goldstone and Green Bank is likely for about 1 week before and after the planned DART impact date of Oct 5.
 - The predicted 7 minute orbit change should be detectable at Goldstone/Green Bank even in echo power spectra.

BACKUP

Goldstone Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (1/2)

| start | date | UTC | Monostatic | | | | | | | | |
|-------|--------|-------------|------------|------|-----------|------|-------|-----|------|-------------|----------|
| | | | Start | Stop | RA | dec | dist | lat | runs | SNR/ | SNR/ |
| | | | | | (degrees) | (au) | (deg) | | day | run | GSSR/GBT |
| 2022 | Sep 25 | 10:07-11:08 | 47 | -34 | 0.078 | -50 | 23 | 33 | 7 | | |
| 2022 | Sep 26 | 09:58-11:33 | 50 | -34 | 0.076 | -50 | 37 | 45 | 8 | | |
| 2022 | Sep 27 | 09:52-11:56 | 53 | -33 | 0.075 | -50 | 49 | 56 | 8 | | |
| 2022 | Sep 28 | 09:47-12:17 | 56 | -32 | 0.074 | -50 | 60 | 66 | 9 | | |
| 2022 | Sep 29 | 09:43-12:38 | 59 | -32 | 0.073 | -49 | 71 | 75 | 9 | | |
| 2022 | Sep 30 | 09:39-12:58 | 62 | -31 | 0.072 | -49 | 82 | 85 | 10 | | |
| 2022 | Oct 01 | 09:35-13:17 | 65 | -30 | 0.072 | -48 | 92 | 93 | 10 | 09:35-10:07 | |
| 2022 | Oct 02 | 09:32-13:36 | 67 | -28 | 0.072 | -47 | 102 | 100 | 10 | 09:32-10:32 | |
| 2022 | Oct 03 | 09:29-13:54 | 70 | -27 | 0.071 | -46 | 112 | 110 | 11 | 09:29-10:55 | |
| 2022 | Oct 04 | 09:26-14:12 | 73 | -26 | 0.071 | -45 | 119 | 110 | 11 | 09:26-11:16 | |
| 2022 | Oct 05 | 09:24-14:28 | 76 | -25 | 0.071 | -44 | 127 | 120 | 11 | 09:24-11:36 | |
| 2022 | Oct 06 | 09:21-14:44 | 78 | -23 | 0.072 | -43 | 135 | 120 | 11 | 09:21-11:54 | |
| 2022 | Oct 07 | 09:18-14:59 | 81 | -22 | 0.072 | -41 | 141 | 120 | 11 | 09:18-12:11 | |
| 2022 | Oct 08 | 09:16-15:13 | 83 | -21 | 0.072 | -40 | 147 | 120 | 11 | 09:16-12:26 | |
| 2022 | Oct 09 | 09:14-15:26 | 86 | -19 | 0.073 | -38 | 152 | 120 | 10 | 09:14-12:41 | |
| 2022 | Oct 10 | 09:11-15:38 | 88 | -18 | 0.074 | -37 | 156 | 120 | 10 | 09:11-12:55 | |
| 2022 | Oct 11 | 09:09-15:50 | 90 | -16 | 0.075 | -35 | 160 | 110 | 10 | 09:09-13:07 | |
| 2022 | Oct 12 | 09:07-16:00 | 92 | -15 | 0.076 | -33 | 162 | 110 | 9 | 09:07-13:19 | |
| 2022 | Oct 13 | 09:05-16:10 | 94 | -13 | 0.077 | -32 | 165 | 100 | 9 | 09:05-13:30 | |
| 2022 | Oct 14 | 09:02-16:19 | 96 | -12 | 0.078 | -30 | 166 | 99 | 8 | 09:02-13:40 | |
| 2022 | Oct 15 | 09:00-16:27 | 98 | -11 | 0.080 | -29 | 168 | 93 | 8 | 09:00-13:49 | |
| 2022 | Oct 16 | 08:58-16:35 | 99 | -9 | 0.081 | -27 | 168 | 88 | 7 | 08:58-13:57 | |
| 2022 | Oct 17 | 08:56-16:42 | 101 | -8 | 0.083 | -26 | 168 | 82 | 7 | 08:56-14:05 | |
| 2022 | Oct 18 | 08:53-16:48 | 103 | -7 | 0.085 | -24 | 168 | 77 | 6 | 08:53-14:12 | |
| 2022 | Oct 19 | 08:51-16:54 | 104 | -6 | 0.086 | -23 | 168 | 72 | 6 | 08:51-14:19 | |
| 2022 | Oct 20 | 08:49-17:00 | 105 | -5 | 0.088 | -22 | 167 | 67 | 6 | 08:49-14:25 | |
| 2022 | Oct 21 | 08:46-17:04 | 107 | -4 | 0.090 | -20 | 166 | 62 | 5 | 08:46-14:30 | |

Goldstone Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (2/2)

| start date | UTC | Monostatic | | | | | | | | | |
|------------|--------|-------------|------|-----------|-------|-------|-----|------|------|-------------|----------|
| | | Start | Stop | RA | dec | dist | lat | runs | SNR/ | SNR/ | GSSR/GBT |
| | | | | | | | | | day | run | Overlap |
| | | | | (degrees) | (au) | (deg) | | | | | |
| 2022 | Oct 22 | 08:44-17:09 | 108 | -3 | 0.092 | -19 | 165 | 57 | 5 | 08:44-14:35 | |
| 2022 | Oct 23 | 08:41-17:13 | 109 | -2 | 0.094 | -18 | 164 | 53 | 5 | 08:41-14:39 | |
| 2022 | Oct 24 | 08:38-17:16 | 110 | -1 | 0.095 | -17 | 163 | 49 | 4 | 08:38-14:43 | |
| 2022 | Oct 25 | 08:36-17:19 | 111 | 0 | 0.097 | -16 | 161 | 46 | 4 | 08:36-14:47 | |
| 2022 | Oct 26 | 08:33-17:22 | 112 | +1 | 0.099 | -15 | 159 | 42 | 4 | 08:33-14:50 | |
| 2022 | Oct 27 | 08:30-17:25 | 113 | +2 | 0.102 | -14 | 158 | 39 | 3 | 08:30-14:53 | |
| 2022 | Oct 28 | 08:28-17:27 | 114 | +3 | 0.104 | -13 | 156 | 36 | 3 | 08:28-14:55 | |
| 2022 | Oct 29 | 08:25-17:29 | 115 | +4 | 0.106 | -12 | 154 | 34 | 3 | 08:25-14:57 | |
| 2022 | Oct 30 | 08:22-17:30 | 116 | +5 | 0.108 | -11 | 153 | 31 | 3 | 08:22-14:59 | |
| 2022 | Oct 31 | 08:19-17:31 | 116 | +5 | 0.110 | -10 | 151 | 29 | 3 | 08:19-15:01 | |
| 2022 | Nov 01 | 08:16-17:32 | 117 | +6 | 0.112 | -9 | 149 | 27 | 2 | | |
| 2022 | Nov 02 | 08:13-17:33 | 118 | +7 | 0.114 | -8 | 147 | 25 | 2 | | |
| 2022 | Nov 03 | 08:09-17:34 | 119 | +7 | 0.116 | -7 | 146 | 23 | 2 | | |
| 2022 | Nov 04 | 08:06-17:34 | 119 | +8 | 0.118 | -7 | 144 | 22 | 2 | | |
| 2022 | Nov 05 | 08:03-17:34 | 120 | +9 | 0.121 | -6 | 142 | 20 | 2 | | |
| 2022 | Nov 06 | 08:00-17:34 | 120 | +9 | 0.123 | -5 | 141 | 19 | 2 | | |
| 2022 | Nov 07 | 07:56-17:34 | 121 | +10 | 0.125 | -4 | 139 | 18 | 2 | | |
| 2022 | Nov 08 | 07:53-17:34 | 121 | +10 | 0.127 | -4 | 137 | 17 | 2 | | |
| 2022 | Nov 09 | 07:49-17:33 | 122 | +11 | 0.129 | -3 | 136 | 16 | 1 | | |
| 2022 | Nov 10 | 07:46-17:33 | 122 | +11 | 0.131 | -3 | 134 | 15 | 1 | | |
| 2022 | Nov 11 | 07:42-17:32 | 123 | +12 | 0.133 | -2 | 133 | 14 | 1 | | |
| 2022 | Nov 12 | 07:38-17:31 | 123 | +12 | 0.135 | -1 | 131 | 13 | 1 | | |
| 2022 | Nov 13 | 07:34-17:30 | 124 | +13 | 0.138 | -1 | 130 | 12 | 1 | | |
| 2022 | Nov 14 | 07:31-17:28 | 124 | +13 | 0.140 | 0 | 128 | 12 | 1 | | |
| 2022 | Nov 15 | 07:27-17:27 | 124 | +14 | 0.142 | 0 | 127 | 11 | 1 | | |
| 2022 | Nov 16 | 07:23-17:25 | 124 | +14 | 0.144 | +1 | 126 | 10 | 1 | | |
| 2022 | Nov 17 | 07:19-17:24 | 125 | +15 | 0.146 | +1 | 124 | 10 | 1 | | |
| 2022 | Nov 18 | 07:15-17:22 | 125 | +15 | 0.148 | +2 | 123 | 9 | 1 | | |

Arecibo Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (1/3)

| UTC | start date | Start | Stop | | | SNR/ | | SNR/ | |
|------|------------|-------------|------|-----------|-------|-------|-----|------|-----|
| | | | | RA | dec | dist | lat | runs | day |
| | | | | (degrees) | (au) | (deg) | | | run |
| 2022 | Oct 24 | 09:16-09:57 | 110 | -1 | 0.095 | -17 | 12 | 230 | 68 |
| 2022 | Oct 25 | 09:05-10:08 | 111 | 0 | 0.097 | -16 | 19 | 291 | 71 |
| 2022 | Oct 26 | 08:58-10:16 | 112 | +1 | 0.099 | -15 | 23 | 319 | 72 |
| 2022 | Oct 27 | 08:52-10:21 | 113 | +2 | 0.101 | -14 | 26 | 335 | 72 |
| 2022 | Oct 28 | 08:47-10:26 | 114 | +3 | 0.103 | -13 | 28 | 341 | 72 |
| 2022 | Oct 29 | 08:42-10:29 | 115 | +4 | 0.105 | -12 | 30 | 342 | 70 |
| 2022 | Oct 30 | 08:38-10:32 | 116 | +4 | 0.107 | -11 | 31 | 332 | 65 |
| 2022 | Oct 31 | 08:34-10:34 | 116 | +5 | 0.110 | -10 | 32 | 319 | 61 |
| 2022 | Nov 01 | 08:31-10:36 | 117 | +6 | 0.112 | -9 | 33 | 304 | 57 |
| 2022 | Nov 02 | 08:27-10:37 | 118 | +7 | 0.114 | -8 | 34 | 290 | 53 |
| 2022 | Nov 03 | 08:24-10:38 | 118 | +7 | 0.116 | -7 | 34 | 273 | 50 |
| 2022 | Nov 04 | 08:21-10:38 | 119 | +8 | 0.118 | -7 | 35 | 259 | 46 |
| 2022 | Nov 05 | 08:18-10:38 | 120 | +9 | 0.120 | -6 | 35 | 245 | 44 |
| 2022 | Nov 06 | 08:15-10:38 | 120 | +9 | 0.122 | -5 | 35 | 231 | 41 |
| 2022 | Nov 07 | 08:12-10:38 | 121 | +10 | 0.125 | -5 | 35 | 218 | 39 |
| 2022 | Nov 08 | 08:08-10:37 | 121 | +10 | 0.127 | -4 | 35 | 205 | 36 |
| 2022 | Nov 09 | 08:05-10:36 | 122 | +11 | 0.129 | -3 | 35 | 194 | 34 |
| 2022 | Nov 10 | 08:02-10:35 | 122 | +11 | 0.131 | -3 | 35 | 183 | 32 |
| 2022 | Nov 11 | 07:59-10:33 | 123 | +12 | 0.133 | -2 | 35 | 173 | 31 |
| 2022 | Nov 12 | 07:56-10:32 | 123 | +12 | 0.135 | -1 | 34 | 162 | 29 |
| 2022 | Nov 13 | 07:53-10:30 | 123 | +13 | 0.137 | -1 | 34 | 154 | 27 |
| 2022 | Nov 14 | 07:50-10:28 | 124 | +13 | 0.139 | 0 | 34 | 146 | 26 |
| 2022 | Nov 15 | 07:47-10:26 | 124 | +14 | 0.141 | 0 | 34 | 138 | 25 |
| 2022 | Nov 16 | 07:43-10:24 | 124 | +14 | 0.144 | +1 | 33 | 130 | 23 |

Arecibo Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (2/3)

| UTC start date | Start | Stop | RA | dec | SNR/ SNR/ | | day | run |
|-------------------|-------------|---------|-------|-----|-------------------|-------------|-----|-----|
| | | | | | dist (degrees) | lat (au) | | |
| 2022 Nov 17 | 07:40-10:22 | 125 +15 | 0.146 | +1 | 33 | 124 | 22 | |
| 2022 Nov 18 | 07:37-10:19 | 125 +15 | 0.148 | +2 | 33 | 117 | 21 | |
| 2022 Nov 19 | 07:33-10:16 | 125 +16 | 0.150 | +2 | 32 | 111 | 20 | |
| 2022 Nov 20 | 07:30-10:14 | 125 +16 | 0.152 | +3 | 32 | 105 | 19 | |
| 2022 Nov 21 | 07:26-10:11 | 126 +17 | 0.154 | +3 | 32 | 100 | 18 | |
| 2022 Nov 22 | 07:23-10:07 | 126 +17 | 0.156 | +4 | 31 | 95 | 18 | |
| 2022 Nov 23 | 07:19-10:04 | 126 +17 | 0.158 | +4 | 30 | 89 | 17 | |
| 2022 Nov 24 | 07:15-10:01 | 126 +18 | 0.160 | +5 | 28 | 82 | 16 | |
| 2022 Nov 25 | 07:12-09:57 | 126 +18 | 0.162 | +5 | 28 | 78 | 15 | |
| 2022 Nov 26 | 07:08-09:54 | 126 +19 | 0.164 | +5 | 28 | 75 | 15 | |
| 2022 Nov 27 | 07:04-09:50 | 126 +19 | 0.166 | +6 | 28 | 72 | 14 | |
| 2022 Nov 28 | 07:00-09:46 | 126 +19 | 0.168 | +6 | 29 | 71 | 14 | |
| 2022 Nov 29 | 06:56-09:42 | 126 +20 | 0.170 | +6 | 29 | 67 | 13 | |
| 2022 Nov 30 | 06:52-09:38 | 126 +20 | 0.172 | +7 | 29 | 64 | 12 | |
| 2022 Dec 01 | 06:48-09:34 | 126 +21 | 0.174 | +7 | 28 | 61 | 12 | |
| 2022 Dec 02 | 06:44-09:29 | 126 +21 | 0.176 | +8 | 28 | 58 | 11 | |
| 2022 Dec 03 | 06:40-09:25 | 126 +21 | 0.179 | +8 | 27 | 55 | 11 | |
| 2022 Dec 04 | 06:36-09:20 | 126 +22 | 0.181 | +8 | 27 | 53 | 11 | |
| 2022 Dec 05 | 06:31-09:16 | 126 +22 | 0.183 | +9 | 27 | 50 | 10 | |
| 2022 Dec 06 | 06:27-09:11 | 125 +22 | 0.185 | +9 | 26 | 48 | 10 | |
| 2022 Dec 07 | 06:22-09:06 | 125 +23 | 0.187 | +9 | 26 | 46 | 9 | |
| 2022 Dec 08 | 06:18-09:01 | 125 +23 | 0.190 | +9 | 25 | 43 | 9 | |
| 2022 Dec 09 | 06:13-08:56 | 125 +23 | 0.192 | +10 | 25 | 41 | 9 | |
| 2022 Dec 10 | 06:09-08:51 | 125 +24 | 0.194 | +10 | 25 | 39 | 8 | |

Arecibo Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (3/3)

| UTC | start date | Start | Stop | SNR/ | | dist | lat | runs | day | run |
|------|------------|-------------|------|-----------|-------|-------|-----|------|-----|-----|
| | | | | RA | dec | | | | | |
| | | | | (degrees) | (au) | (deg) | | | | |
| 2022 | Dec 11 | 06:04-08:46 | 124 | +24 | 0.197 | +10 | 24 | 37 | 8 | |
| 2022 | Dec 12 | 06:00-08:40 | 124 | +24 | 0.199 | +10 | 24 | 35 | 8 | |
| 2022 | Dec 13 | 05:55-08:35 | 124 | +25 | 0.202 | +11 | 23 | 33 | 7 | |
| 2022 | Dec 14 | 05:50-08:29 | 123 | +25 | 0.204 | +11 | 23 | 32 | 7 | |
| 2022 | Dec 15 | 05:45-08:24 | 123 | +25 | 0.207 | +11 | 23 | 30 | 7 | |
| 2022 | Dec 16 | 05:40-08:18 | 123 | +26 | 0.210 | +11 | 22 | 28 | 6 | |
| 2022 | Dec 17 | 05:36-08:12 | 122 | +26 | 0.212 | +12 | 22 | 27 | 6 | |
| 2022 | Dec 18 | 05:31-08:06 | 122 | +26 | 0.215 | +12 | 21 | 25 | 6 | |
| 2022 | Dec 19 | 05:26-08:00 | 122 | +27 | 0.218 | +12 | 21 | 24 | 5 | |
| 2022 | Dec 20 | 05:21-07:54 | 121 | +27 | 0.221 | +12 | 21 | 23 | 5 | |
| 2022 | Dec 21 | 05:16-07:49 | 121 | +27 | 0.224 | +12 | 20 | 21 | 5 | |
| 2022 | Dec 22 | 05:11-07:42 | 121 | +27 | 0.227 | +13 | 20 | 20 | 5 | |
| 2022 | Dec 23 | 05:06-07:36 | 120 | +28 | 0.230 | +13 | 19 | 19 | 5 | |
| 2022 | Dec 24 | 05:00-07:30 | 120 | +28 | 0.234 | +13 | 19 | 18 | 4 | |
| 2022 | Dec 25 | 04:55-07:24 | 119 | +28 | 0.237 | +13 | 19 | 17 | 4 | |
| 2022 | Dec 26 | 04:50-07:18 | 119 | +28 | 0.241 | +13 | 18 | 16 | 4 | |
| 2022 | Dec 27 | 04:45-07:12 | 118 | +28 | 0.244 | +13 | 18 | 15 | 4 | |
| 2022 | Dec 28 | 04:40-07:06 | 118 | +29 | 0.248 | +13 | 17 | 14 | 3 | |
| 2022 | Dec 29 | 04:35-07:00 | 118 | +29 | 0.252 | +13 | 17 | 13 | 3 | |
| 2022 | Dec 30 | 04:29-06:54 | 117 | +29 | 0.256 | +14 | 17 | 12 | 3 | |
| 2022 | Dec 31 | 04:24-06:48 | 117 | +29 | 0.260 | +14 | 16 | 11 | 3 | |
| 2023 | Jan 01 | 04:19-06:41 | 116 | +29 | 0.264 | +14 | 16 | 11 | 3 | |
| 2023 | Jan 02 | 04:14-06:35 | 116 | +30 | 0.269 | +14 | 15 | 10 | 3 | |
| 2023 | Jan 03 | 04:08-06:29 | 115 | +30 | 0.273 | +14 | 15 | 9 | 3 | |
| 2023 | Jan 04 | 04:03-06:23 | 115 | +30 | 0.278 | +14 | 15 | 9 | 2 | |

Goldstone Signal-to-Noise Ratios for the Secondary during the 2022 radar apparition

| start | date | UTC | | | dist | lat | runs | SNR/ | |
|-------|--------|-------|--------|--------|-------|-----|------|------|---------|
| | | Start | Stop | RA dec | | | | day | SNR/run |
| 2022 | Sep 25 | 10:07 | -11:08 | 47 -34 | 0.078 | -50 | 23 | 6 | 1 |
| 2022 | Sep 26 | 09:58 | -11:33 | 50 -34 | 0.076 | -50 | 37 | 9 | 1 |
| 2022 | Sep 27 | 09:52 | -11:56 | 53 -33 | 0.075 | -50 | 49 | 11 | 2 |
| 2022 | Sep 28 | 09:47 | -12:17 | 56 -32 | 0.074 | -50 | 60 | 12 | 2 |
| 2022 | Sep 29 | 09:43 | -12:38 | 59 -32 | 0.073 | -49 | 71 | 14 | 2 |
| 2022 | Sep 30 | 09:39 | -12:58 | 62 -31 | 0.072 | -49 | 82 | 16 | 2 |
| 2022 | Oct 01 | 09:35 | -13:17 | 65 -30 | 0.072 | -48 | 92 | 18 | 2 |
| 2022 | Oct 02 | 09:32 | -13:36 | 67 -28 | 0.072 | -47 | 102 | 19 | 2 |
| 2022 | Oct 03 | 09:29 | -13:54 | 70 -27 | 0.071 | -46 | 111 | 20 | 2 |
| 2022 | Oct 04 | 09:26 | -14:12 | 73 -26 | 0.071 | -45 | 119 | 21 | 2 |
| 2022 | Oct 05 | 09:24 | -14:28 | 76 -25 | 0.071 | -44 | 127 | 22 | 2 |
| 2022 | Oct 06 | 09:21 | -14:44 | 78 -23 | 0.072 | -43 | 135 | 23 | 2 |
| 2022 | Oct 07 | 09:18 | -14:59 | 81 -22 | 0.072 | -41 | 141 | 23 | 2 |
| 2022 | Oct 08 | 09:16 | -15:13 | 83 -21 | 0.072 | -40 | 147 | 23 | 2 |
| 2022 | Oct 09 | 09:14 | -15:26 | 86 -19 | 0.073 | -38 | 152 | 23 | 2 |
| 2022 | Oct 10 | 09:11 | -15:38 | 88 -18 | 0.074 | -37 | 156 | 22 | 2 |
| 2022 | Oct 11 | 09:09 | -15:50 | 90 -16 | 0.075 | -35 | 160 | 21 | 2 |
| 2022 | Oct 12 | 09:07 | -16:00 | 92 -15 | 0.076 | -33 | 162 | 21 | 2 |
| 2022 | Oct 13 | 09:05 | -16:10 | 94 -13 | 0.077 | -32 | 165 | 20 | 2 |
| 2022 | Oct 14 | 09:02 | -16:19 | 96 -12 | 0.078 | -30 | 166 | 19 | 2 |
| 2022 | Oct 15 | 09:00 | -16:27 | 98 -11 | 0.080 | -29 | 168 | 18 | 2 |
| 2022 | Oct 16 | 08:58 | -16:35 | 99 -9 | 0.081 | -27 | 168 | 17 | 1 |
| 2022 | Oct 17 | 08:56 | -16:42 | 101 -8 | 0.083 | -26 | 168 | 16 | 1 |
| 2022 | Oct 18 | 08:53 | -16:48 | 103 -7 | 0.085 | -24 | 168 | 15 | 1 |
| 2022 | Oct 19 | 08:51 | -16:54 | 104 -6 | 0.086 | -23 | 168 | 14 | 1 |
| 2022 | Oct 20 | 08:49 | -17:00 | 105 -5 | 0.088 | -22 | 167 | 13 | 1 |
| 2022 | Oct 21 | 08:46 | -17:04 | 107 -4 | 0.090 | -20 | 166 | 12 | 1 |
| 2022 | Oct 22 | 08:44 | -17:09 | 108 -3 | 0.092 | -19 | 165 | 11 | 1 |
| 2022 | Oct 23 | 08:41 | -17:13 | 109 -2 | 0.094 | -18 | 164 | 10 | 1 |
| 2022 | Oct 24 | 08:38 | -17:16 | 110 -1 | 0.095 | -17 | 163 | 9 | 1 |

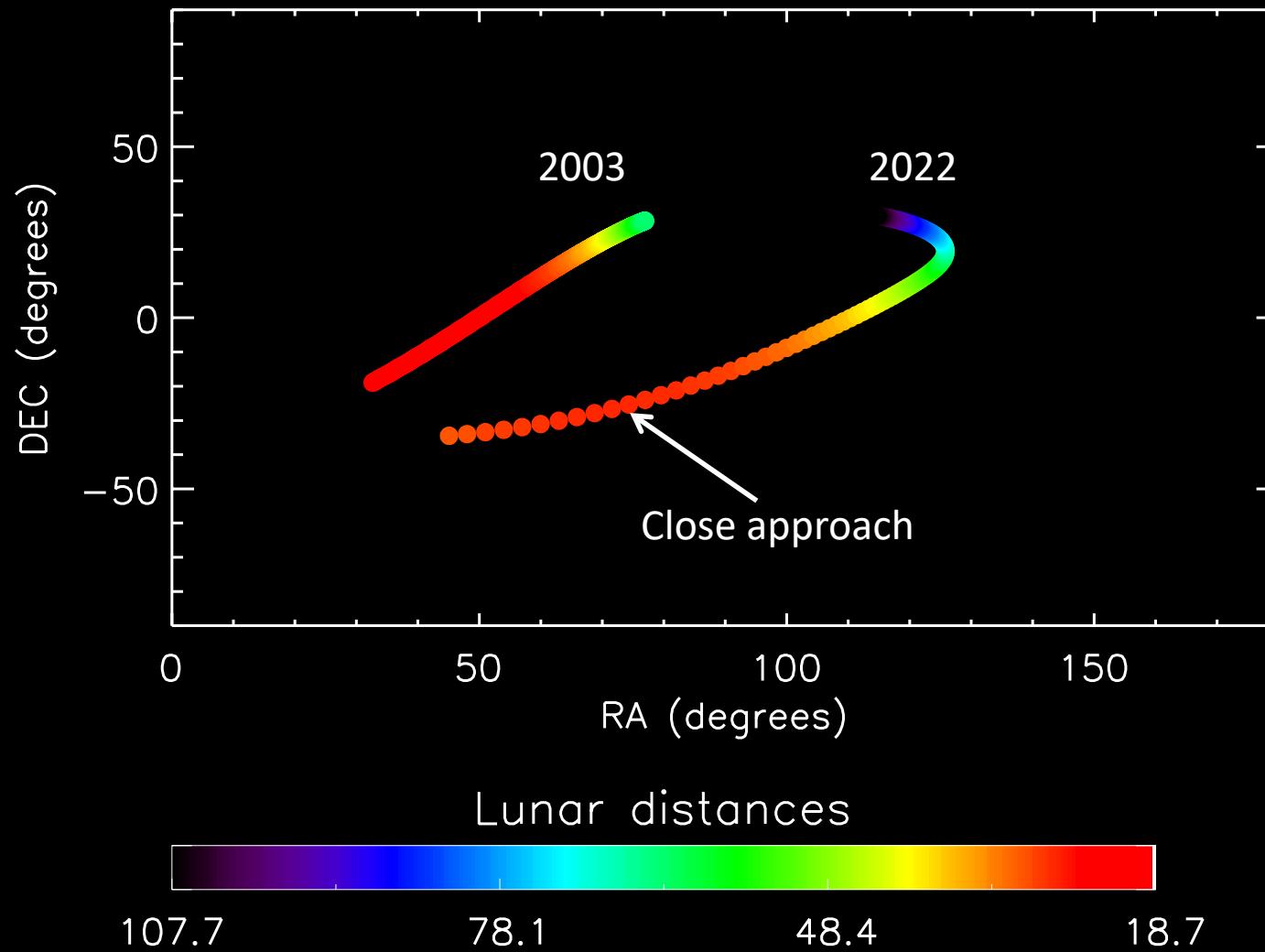
Arecibo Signal-to-Noise Ratios for the Secondary during the 2022 radar apparition (1/2)

| | UTC | | | | | | SNR/ | | | |
|-------|--------|-------|--------|-----|-----|-------|------|------|-----|-----|
| start | date | Start | Stop | RA | dec | dist | lat | runs | day | run |
| 2022 | Oct 24 | 09:16 | -09:57 | 110 | -1 | 0.095 | -17 | 12 | 44 | 13 |
| 2022 | Oct 25 | 09:05 | -10:08 | 111 | 0 | 0.097 | -16 | 19 | 55 | 13 |
| 2022 | Oct 26 | 08:58 | -10:16 | 112 | +1 | 0.099 | -15 | 23 | 61 | 14 |
| 2022 | Oct 27 | 08:52 | -10:21 | 113 | +2 | 0.101 | -14 | 26 | 64 | 14 |
| 2022 | Oct 28 | 08:47 | -10:26 | 114 | +3 | 0.103 | -13 | 28 | 65 | 14 |
| 2022 | Oct 29 | 08:42 | -10:29 | 115 | +4 | 0.105 | -12 | 30 | 65 | 13 |
| 2022 | Oct 30 | 08:38 | -10:32 | 116 | +4 | 0.107 | -11 | 31 | 63 | 12 |
| 2022 | Oct 31 | 08:34 | -10:34 | 116 | +5 | 0.110 | -10 | 32 | 60 | 12 |
| 2022 | Nov 01 | 08:31 | -10:36 | 117 | +6 | 0.112 | -9 | 33 | 58 | 11 |
| 2022 | Nov 02 | 08:27 | -10:37 | 118 | +7 | 0.114 | -8 | 34 | 55 | 10 |
| 2022 | Nov 03 | 08:24 | -10:38 | 118 | +7 | 0.116 | -7 | 34 | 52 | 9 |
| 2022 | Nov 04 | 08:21 | -10:38 | 119 | +8 | 0.118 | -7 | 35 | 49 | 9 |
| 2022 | Nov 05 | 08:18 | -10:38 | 120 | +9 | 0.120 | -6 | 35 | 46 | 8 |
| 2022 | Nov 06 | 08:15 | -10:38 | 120 | +9 | 0.122 | -5 | 35 | 44 | 8 |
| 2022 | Nov 07 | 08:12 | -10:38 | 121 | +10 | 0.125 | -5 | 35 | 41 | 7 |
| 2022 | Nov 08 | 08:08 | -10:37 | 121 | +10 | 0.127 | -4 | 35 | 39 | 7 |
| 2022 | Nov 09 | 08:05 | -10:36 | 122 | +11 | 0.129 | -3 | 35 | 37 | 7 |
| 2022 | Nov 10 | 08:02 | -10:35 | 122 | +11 | 0.131 | -3 | 35 | 35 | 6 |
| 2022 | Nov 11 | 07:59 | -10:33 | 123 | +12 | 0.133 | -2 | 35 | 33 | 6 |
| 2022 | Nov 12 | 07:56 | -10:32 | 123 | +12 | 0.135 | -1 | 34 | 31 | 5 |
| 2022 | Nov 13 | 07:53 | -10:30 | 123 | +13 | 0.137 | -1 | 34 | 29 | 5 |
| 2022 | Nov 14 | 07:50 | -10:28 | 124 | +13 | 0.139 | 0 | 34 | 28 | 5 |
| 2022 | Nov 15 | 07:47 | -10:26 | 124 | +14 | 0.141 | 0 | 34 | 26 | 5 |

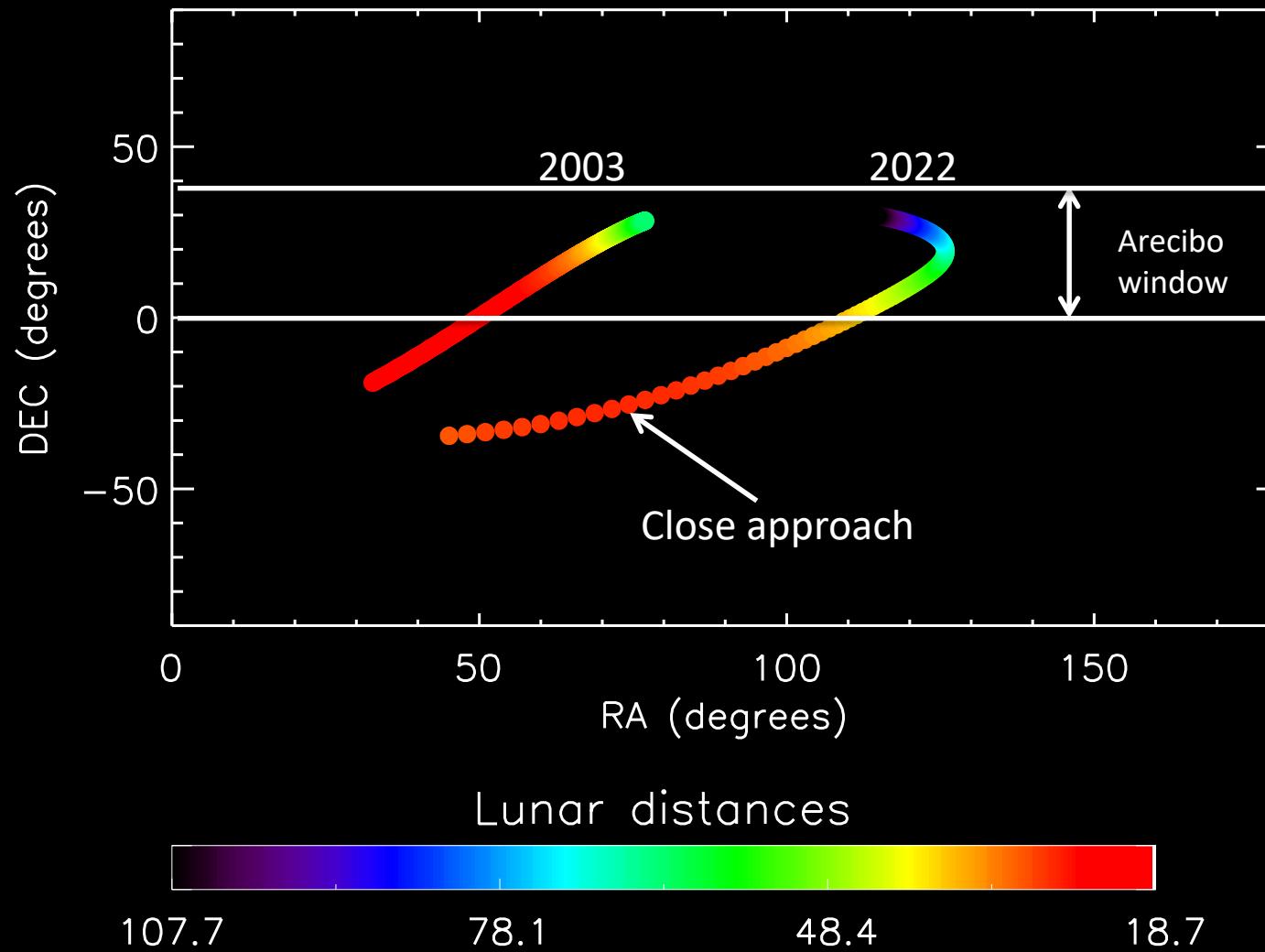
Arecibo Signal-to-Noise Ratios for the
Secondary during the 2022 radar apparition
(2/2)

| | UTC | | | | | | SNR/ | SNR/ | | |
|-------|--------|-------------|---------|-------|-----|------|------|------|-----|-----|
| start | date | Start | Stop | RA | dec | dist | lat | runs | day | run |
| 2022 | Nov 16 | 07:43-10:24 | 124 +14 | 0.144 | +1 | 33 | 25 | 4 | | |
| 2022 | Nov 17 | 07:40-10:22 | 125 +15 | 0.146 | +1 | 33 | 23 | 4 | | |
| 2022 | Nov 18 | 07:37-10:19 | 125 +15 | 0.148 | +2 | 33 | 22 | 4 | | |
| 2022 | Nov 19 | 07:33-10:16 | 125 +16 | 0.150 | +2 | 32 | 21 | 4 | | |
| 2022 | Nov 20 | 07:30-10:14 | 125 +16 | 0.152 | +3 | 32 | 20 | 4 | | |
| 2022 | Nov 21 | 07:26-10:11 | 126 +17 | 0.154 | +3 | 32 | 19 | 3 | | |
| 2022 | Nov 22 | 07:23-10:07 | 126 +17 | 0.156 | +4 | 31 | 18 | 3 | | |
| 2022 | Nov 23 | 07:19-10:04 | 126 +17 | 0.158 | +4 | 30 | 17 | 3 | | |
| 2022 | Nov 24 | 07:15-10:01 | 126 +18 | 0.160 | +5 | 28 | 16 | 3 | | |
| 2022 | Nov 25 | 07:12-09:57 | 126 +18 | 0.162 | +5 | 28 | 15 | 3 | | |
| 2022 | Nov 26 | 07:08-09:54 | 126 +19 | 0.164 | +5 | 28 | 14 | 3 | | |
| 2022 | Nov 27 | 07:04-09:50 | 126 +19 | 0.166 | +6 | 28 | 14 | 3 | | |
| 2022 | Nov 28 | 07:00-09:46 | 126 +19 | 0.168 | +6 | 29 | 13 | 3 | | |
| 2022 | Nov 29 | 06:56-09:42 | 126 +20 | 0.170 | +6 | 29 | 13 | 2 | | |
| 2022 | Nov 30 | 06:52-09:38 | 126 +20 | 0.172 | +7 | 29 | 12 | 2 | | |
| 2022 | Dec 01 | 06:48-09:34 | 126 +21 | 0.174 | +7 | 28 | 12 | 2 | | |
| 2022 | Dec 02 | 06:44-09:29 | 126 +21 | 0.176 | +8 | 28 | 11 | 2 | | |
| 2022 | Dec 03 | 06:40-09:25 | 126 +21 | 0.179 | +8 | 27 | 10 | 2 | | |
| 2022 | Dec 04 | 06:36-09:20 | 126 +22 | 0.181 | +8 | 27 | 10 | 2 | | |
| 2022 | Dec 05 | 06:31-09:16 | 126 +22 | 0.183 | +9 | 27 | 10 | 2 | | |
| 2022 | Dec 06 | 06:27-09:11 | 125 +22 | 0.185 | +9 | 26 | 9 | 2 | | |

Observing geometry in 2022

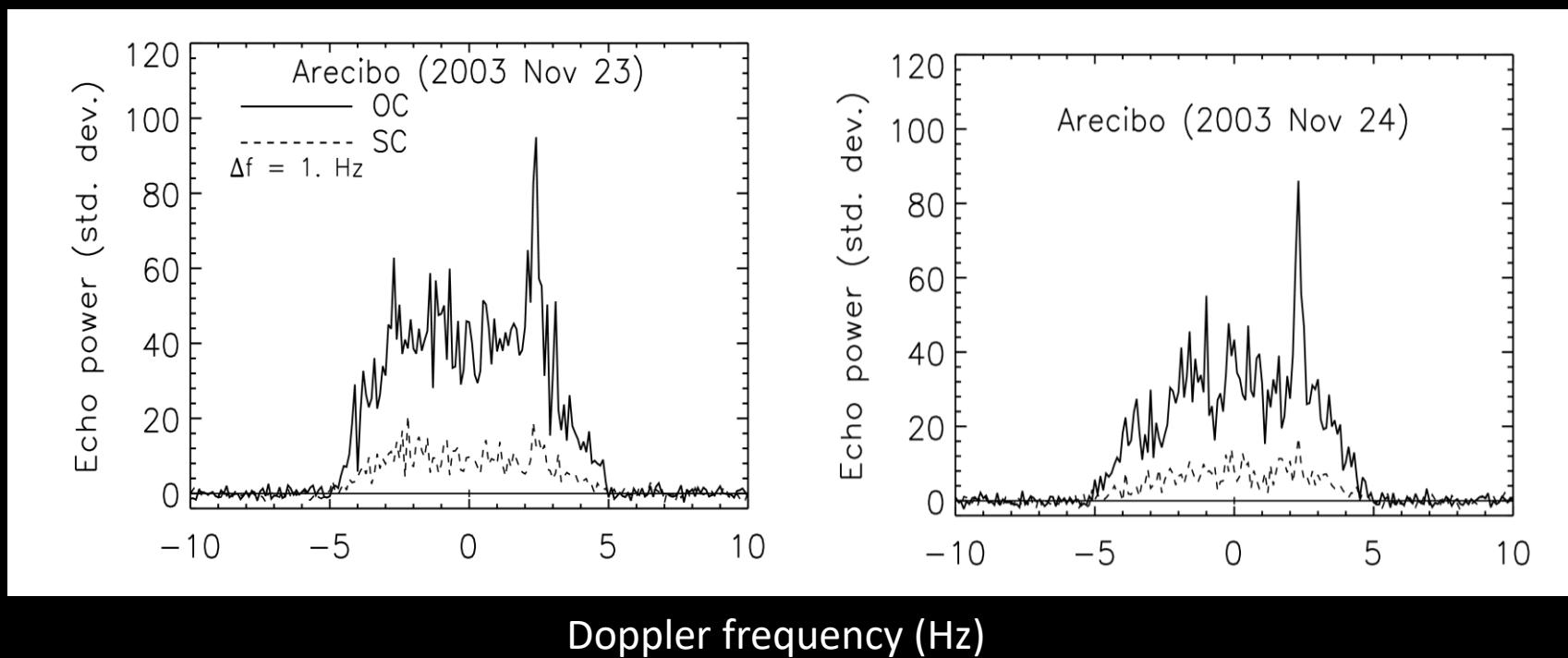


Observing geometry in 2022



Arecibo echo power spectra from 2003

Echo power (std. dev of noise)

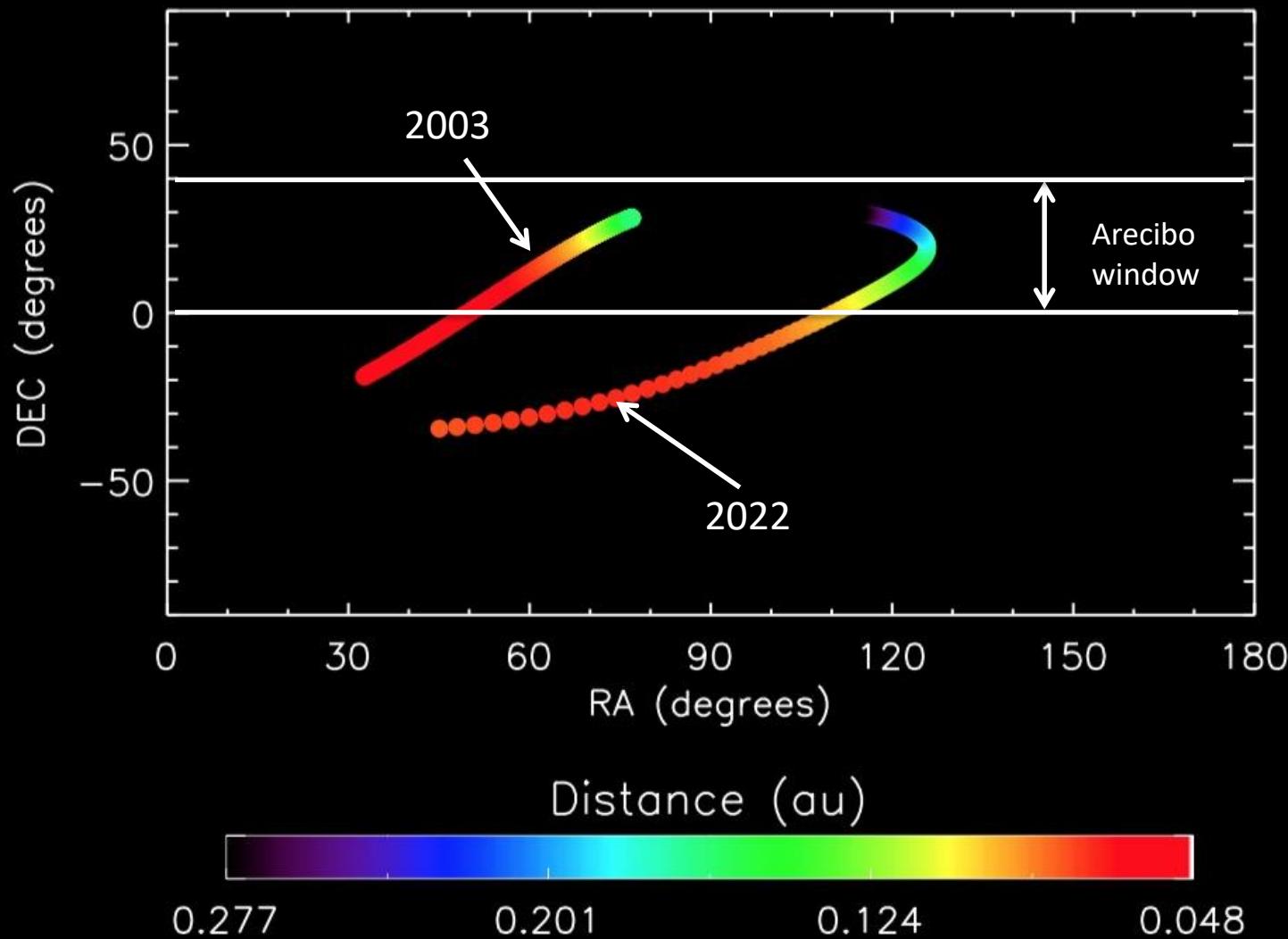


The strongest Arecibo SNRs in 2022 will be 1/6th of those shown here

Radar opportunity in 2022

- Earth close approach on October 4
 - Encounter distance will be 0.071 au (1.5 x the 2003 close approach)
- Goldstone target: Sep 25 – Nov 18
 - Maximum SNR 1/4th as strong as 2003
- Arecibo target from Oct 24 – Jan 04
 - Maximum SNR 1/3rd as strong as 2003

Observing geometry in 2022



Goldstone primary SNRs

| UTC start date | RA, dec | dist | lat | SNR/ day | SNR/ run |
|-------------------|---------|-------|-----|-------------|-------------|
| 2022 Sep 25 | 47, -34 | 0.078 | -50 | 33 | 7 |
| : | | | | | |
| 2022 Oct 03 | 70, -27 | 0.071 | -46 | 110 | 11 |
| 2022 Oct 04 | 73, -26 | 0.071 | -45 | 110 | 11 |
| 2022 Oct 05 | 76, -25 | 0.071 | -44 | 120 | 11 |
| 2022 Oct 06 | 78, -23 | 0.072 | -43 | 120 | 11 |
| 2022 Oct 07 | 81, -22 | 0.072 | -41 | 120 | 11 |
| 2022 Oct 08 | 83, -21 | 0.072 | -40 | 120 | 11 |
| : | | | | | |
| 2022 Nov 18 | 125, 15 | 0.148 | +2 | 9 | 1 |

Secondary SNRs will be 1/6th of the primary SNRs

Arecibo primary SNRs

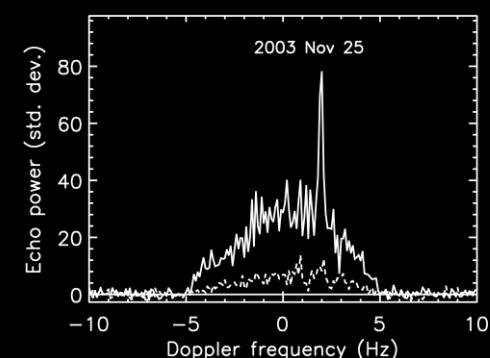
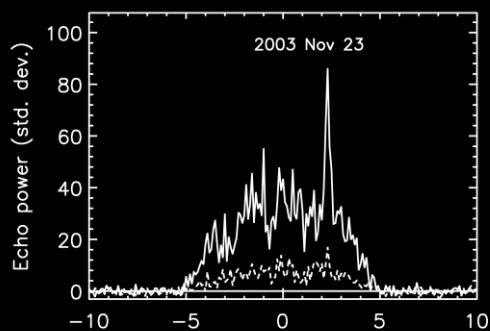
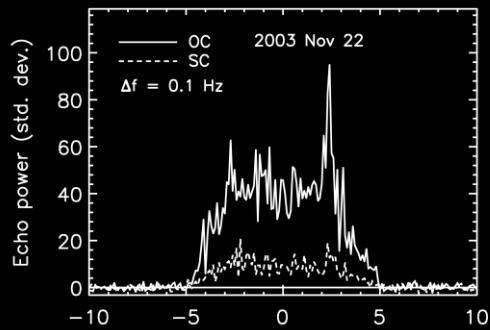
| UTC start date | RA, dec | dist | lat | SNR/ day | SNR/ run |
|-------------------|----------|-------|-----|-------------|-------------|
| 2022 Oct 25 | 111, 0 | 0.097 | -16 | 291 | 71 |
| 2022 Oct 26 | 112, +1 | 0.099 | -15 | 319 | 72 |
| 2022 Oct 27 | 113, +2 | 0.101 | -14 | 335 | 72 |
| 2022 Oct 28 | 114, +3 | 0.103 | -13 | 341 | 72 |
| 2022 Oct 29 | 115, +4 | 0.105 | -12 | 342 | 70 |
| 2022 Oct 30 | 116, +4 | 0.107 | -11 | 332 | 65 |
| 2022 Oct 31 | 116, +5 | 0.110 | -10 | 319 | 61 |
| 2022 Nov 01 | 117, +6 | 0.112 | -9 | 304 | 57 |
| 2022 Nov 02 | 118, +7 | 0.114 | -8 | 290 | 53 |
| 2022 Nov 03 | 118, +7 | 0.116 | -7 | 273 | 50 |
| 2022 Nov 04 | 119, +8 | 0.118 | -7 | 259 | 46 |
| 2022 Nov 05 | 120, +9 | 0.120 | -6 | 245 | 44 |
| : | | | | | |
| 2023 Jan 04 | 115, +30 | 0.278 | +14 | 9 | 2 |

Radar opportunity in 2022

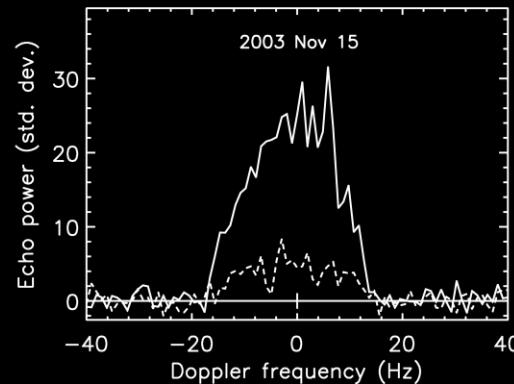
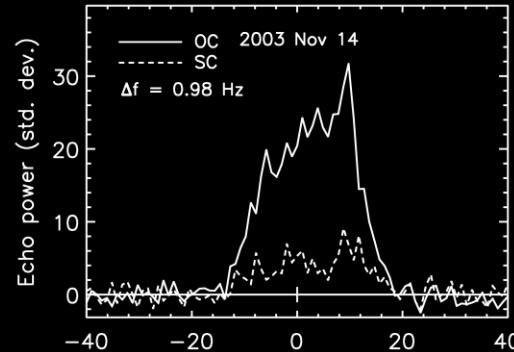
- Resolutions: 2x coarser than those in 2003
 - Goldstone: 150 m/pixel
 - Arecibo: 30 m/pixel
- Using GBT to receive Goldstone signals will improve resolution to 75 m/pixel

Echo power spectra

Arecibo



Goldstone



S-band (Arecibo):

OC albedo = $0.20 \pm 25\%$

SC/OC = $0.22 \pm 20\%$

X-band (Goldstone):

OC albedo = $0.30 \pm 35\%$

SC/OC = $0.20 \pm 30\%$

=> Surface/near-surface density = 1000 kg/m^3